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Cosmic Ray Effects on Microelectronics

Part III: Propagation of Cosmic Rays in the Atmosphere

C. H. TSAO, R. SILBERBERG, J. H. ADAMS, JR., AND J. R. LETAW*

E. O. Hulburt Center for Space Research
Space Science Division

**Severn Communications Corporation*
Severna Park, MD 21146

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Tsao, C.H., Silberberg, R., Adams, J.H., Jr., and Letaw, J.R.*

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Cosmic-ray nuclei that enter the atmosphere will subsequently breakup into lighter nuclei due to collisions with air particles. They also undergo a gradual loss of energy due to ionization. The fluxes and energy spectra of particles were calculated for several atmospheric depths and geomagnetic locations. The results of these radiation transport calculations are plotted as integral LET-spectra showing the total number of particles that can contribute to energy lows in silicon above a given threshold value. The results can then be used to calculate the upset rate induced by cosmic ray nuclei for devices of known size and critical charge.

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COSMIC RAY EFFECTS ON MICROELECTRONICS

Part III: Propagation of Cosmic Rays in the Atmosphere

1.0. Introduction:

This report considers the propagation of primary cosmic rays through the atmosphere and assesses their effectiveness at producing single event upsets (SEU) in microelectronic components. The problem of soft upsets centers on the ability of a single charged particle, upon passage through a sensitive volume on a silicon chip, to cause the logical state of a memory circuit to change. Such upsets obviously have immense leverage in, for example, control circuit applications. Shielding against cosmic-ray-induced upsets is difficult because they are highly penetrating and have measurable fluxes at extremely high energies. The upset potential of cosmic rays is dependent on many factors including the solar cycle, geomagnetic field strength, atmospheric depth, and device orientation. In this report upset calculations in the atmosphere are described and computer code to perform these calculations is presented.

In Section 2 we consider the effect of passage through air on cosmic ray fluxes. The most prominent interactions with air are nuclear fragmentation reactions and ionization loss. Close collisions between air nuclei and cosmic rays cause breakup of the cosmic ray into lighter nuclides. Generally a few nucleons or alpha particles are emitted. The fragments retain roughly the same energy/nucleon as the incident nucleus. Secondaries, that is, accelerated fragments of silicon nuclei are not considered in this report although they are a potential source of upsets (Peterson, 1981). Leptons and mesons created in the collisions are also not considered.

Distant collisions between air molecules and cosmic rays do not change the composition. They generally cause ionization of the air. These collisions gradually decelerate the cosmic rays and modify their spectrum. The rate of energy loss, or stopping power, is proportional to the square of the cosmic ray charge. Thus the heavy ions which are most effective at causing upsets suffer greatest attenuation in the atmosphere. Nuclear decay need not be considered because propagation through the atmosphere takes a fraction of a millisecond while most decays occur on time scales of more than milliseconds.

In Section 3 results of cosmic ray propagation through air are integrated to give total flux levels at any altitude. This integration involves calculating flux levels as a function of zenith and azimuthal angles. These depend on the geomagnetic field and the amount of air to the top of the atmosphere in any direction. The latter is a sec θ effect for the altitudes considered in this report. The geomagnetic field effect results in an enhancement of fluxes to the west relative to the vertical. Total cosmic ray fluxes as a function of altitude and cutoff are displayed showing the roughly exponential decrease as a function of both variables.

Section 4 considers the conversion of cosmic ray spectra into LET (linear energy transfer) spectra and upset computations. LET spectra show the flux as a function of stopping power in silicon. Instead of

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classifying according to energy, they are classified according to the rate at which they give up energy in silicon. As stated previously LET increases as the square of the cosmic ray charge. LET is not a monotonic function of energy. In fact the lowest LET occurs at high energies (a few GeV/nucleon) while the highest LET occurs at a few MeV/nucleon. The stopping powers vary by roughly a factor of 50 in this range. LET spectra for geomagnetic cutoffs ranging from 0 to 8 GV, and altitudes between 55,000 and 150,000 ft. are presented.

Given the device parameters, LET spectra may be converted into upset probabilities. In any environment the probability of upset depends on a critical charge and sensitive volume (device dependent parameters) in addition to the cosmic ray LET spectrum. The critical charge is the number of free electron-hole pairs necessary in the neighborhood of a junction to cause an upset. These pairs are created at a rate of one per 3.6 eV of deposited energy. The sensitive volume is characterized by a chord length distribution giving the relative frequency of each pathlength. The energy deposited is proportional to this pathlength.

Section 5 consists of descriptions of the programs developed to estimate soft upsets in the atmosphere.

2.0. Propagation of Cosmic Rays through Air

2.1 Master Propagation Equation

The cosmic ray flux at the top of the atmosphere consists roughly of 2500 proton/(m^2 sec ster), about one tenth as many He nuclei, and roughly 1 per cent heavier nuclei. The average energy of these particles is 1 or 2 GeV/nucleon. Within the magnetosphere and atmosphere they are subject to several attenuating processes. The most important are:

1) Fragmentation in collision with N and O nuclei in the air.
2) Energy loss by ionization of the air.
3) Deflection from the atmosphere by the geomagnetic field.

The first two of these processes are discussed in this section, while the third is discussed in Section 3.

The master equation for cosmic ray propagation with ionization loss and fragmentation (Ginzburg and Syrovatskii, 1964) is:

$$\frac{\partial J_i}{\partial t} = - n v \sigma_i J_i + n v \sum_{j>i} \sigma_{ij} J_j + \frac{\partial}{\partial E} \left(\frac{dE}{dt} \quad \frac{J_i}{A_i} \right) \qquad (2.1\text{-}1)$$

Terms in this equation are defined as follows:

J_i = Differential energy spectrum of cosmic rays of species i in particles/m^2 sec steradian (MeV/nucleon). If species are ordered by increasing mass, and within that by decreasing charge, then all reactions reduce the species index. For example, $^6Li < {^7Be} < {^7Li}$.

σ_i = Total reaction cross-section for nuclei of species i in air.

σ_{ij} = Partial fragmentation cross-sections for nuclei of species i to be produced in collisions of species j with air.

n = Number density of N and O nuclei in air.

v = Cosmic ray velocity which is related to energy/nucleon (MeV/nucleon) by

$$(v/c)^2 = \frac{E(E + 1863)}{(E + 931.5)^2}$$

A_i = Atomic mass of species i.

It is convenient to re-express eq. 2.1-1 in terms of pathlength, instead of time. The pathlength is the total number of grams of material in a cylinder of 1 cm^2 cross section traversed in time, t, by the particle. Thus,

$$x \; (g/cm^2) = n \; v \; m \; t \qquad (2.1\text{-}2)$$

where m is the average mass of an air atom. The pathlength between the top of the atmosphere and any point directly below is essentially equal to the air pressure at that point. However, pathlength has units of mass per unit area while pressure is force per unit area. The relation between pathlength and altitude is shown in Fig. 2.1. Data for this figure were taken from the 1962 U. S. Standard Atmosphere (NASA et al., 1962). A fit to the data valid between 50 and 150 kilofeet is also shown. Table 2.1 shows altitude vs. pathlength comparisons of special interest in this report. The composition of the atmosphere is essentially constant in the region of interest. We assume a mixture consisting of 79 per cent N and 21 per cent O by number.

Table 2.1
ALTITUDE vs. PATHLENGTH
(corresponding to computations in this report)

Altitude		Pathlength
kilofeet	kilometers	g/cm^2
150	45.7	1.33
125	38.1	3.59
100	30.5	11.1
85	25.9	22.0
75	22.9	35.0
65	19.8	56.5
60	18.3	72.1
55	16.3	92.2

In terms of pathlength Eq. 2.1-1 may be rewritten:

$$\frac{\partial J_i}{\partial x} = -\frac{\sigma_i\ J_i}{23954} + \sum_{j>i} \frac{\sigma_{ij}\ J_j}{23954} + \frac{1}{A_i}\ \frac{\partial}{\partial E}\left(w_i J_i\right), \qquad (2.1\text{-}3)$$

where w_i is the stopping power of nuclei of species; 'n air. This fixes the cross section units to millibarns and the stopping power units to MeV/(g/cm^2). The factor 23954 is the average mass in grams of an air nucleus divided by the unit conversion from cm^2 to mb.

For the purposes of further manipulation we express Eq. 2.1-3 in the condensed, matrix form:

$$\frac{\partial J}{\partial x} = M\ J + \frac{\partial}{\partial E}(\bar{w}\ \ J) \qquad (2.1\text{-}4)$$

The fragmentation effects are contained in the modification matrix, M, and ionization loss effects in the derivative term; $\overline{w}$ is the energy less per nucleon.

Approximating the ionization loss and backsubstituting for K we have the approximate solution:

$$(2.1\text{-}5)$$

$$J(E,x+\Delta x) = e^{M\Delta x}\left\{\left[1 - \overline{w}(E)\ \frac{\Delta x}{\Delta E}\right] J(E,x) + \overline{w}\ (E + \Delta E)\frac{\Delta x}{\Delta E}\ \ J(E + \Delta E,x)\right\}$$

In this form the flux at a given pathlength and energy depends only on the flux at shorter pathlengths and greater (or equal) energies.

The flux at the highest energy, where ionization loss can be linearized (Letaw et al., 1983b), is:

$$J(E_{max},\ x) = e^{Mx}\ J(E_{max},\ 0) \qquad (2.1\text{-}6)$$

where M now contains the term:

$$-(n\alpha\ \ - n + 1)\ \frac{Z_i^{\ 2}}{A_i R_p} \qquad (2.1\text{-}7)$$

R_p is the proton range in air, Z_i the charge of species i, n the range-energy index (~ 1), and α the spectral index (~ 2.7) of the differential flux at high energy. The relative importance of this term is gauged by comparison with fragmentation losses.

2.2 List of Isotopic Species

The most abundant cosmic rays have charges between 1 and 28. Heavier elements exist in much smaller quantities because they are beyond the stability point at iron for stellar nucleosynthesis. A list of 230 isotopes from H through Fe was extracted from the Table of Isotopes (Lederer and Shirley, 1978). Most of these isotopes are unstable but cannot decay during the fraction of a millisecond spent in the atmosphere.

To reduce the length of the list, a propagation through air (neglecting ionization loss) with pathlength of 30 g/cm^2 was performed. Elemental abundances were taken from Adams, et al. (1981). Isotopic abundances were estimated from recent data (Webber, 1981; Young et al., 1981; Garcia-Munoz et al., 1981). Unstable isotopes are created in fragmentation reactions. Those which did not achieve an abundance greater than or equal to 1 percent that of Fe were dropped from the list. Those which developed abundances between 1 percent and 5 percent of iron were regrouped with other isotopes of the same charge. In this way a reduced list of 104 isotopes was developed (Table 2.2).

2.3 Cross Sections

Two sets of cross sections, the total reaction cross sections σ_i and the partial fragmentation cross sections σ_{ij}, are needed to perform air propagation calculations. These cross sections are for reactions of the form:

$$\text{Nuclide} + \begin{Bmatrix} N \\ O \end{Bmatrix} \rightarrow \text{anything}$$

Roughly 5500 partial cross sections and 104 total cross sections are required. These cross sections are incompletely known and are estimated using semi-empirical formulas.

The partial cross sections for many proton-nucleus reactions are given by the semi-empirical formulas (Silberberg and Tsao, 1973a,b; Silberberg and Tsao, 1977a; Tsao, et al., 1983). These are scaled up to air-nucleus interactions using procedures discussed in Silberberg and Tsao (1977b). The scale factor is roughly 2 with additional enhancement for light products.

The total cross sections are calculated using the Bradt-Peters (1950) overlap model:

$$\sigma = 49.88\ (A_t^{\ 1/3} + A_p^{\ 1/3} - 0.4)^2 \qquad (2.3\text{-}1)$$

where A_t and A_p are the target and projectile masses respectively.

Table 2.2

Isotope	Progenitors	Fraction of Elemental Abundance
1H 1	5B 9	1.000
1H 2		0.000
2HE 3		0.000
1H 3		0.000
2HE 4	4BE 8 4BE 8 5B 9 5B 9	1.000
3LI 5		0.000
2HE 5		0.000
3LI 6		0.500
2HE 6		0.000
4BE 7		0.500
3LI 7	3LI 8 3LI 9	0.500
2HE 8		0.000
4BE 9		0.500
5B 10	5B 8	0.250
4BE 10	4BE 11 4BE 12	0.000
6C 11	6C 9 6C 10	0.000
5B 11	5B 12 5B 13 5B 14	0.750
6C 12		1.000
6C 13	6C 14 6C 15 6C 16	0.000
7N 14	7N 12 7N 13	0.500
8O 15	8O 13 8O 14	0.000
7N 15	7N 16 7N 17 7N 18	0.500
8O 16	8O 17 8O 18 8O 19 8O 20	1.000
9F 17		0.000
9F 18		0.000
10NE 19	10NE 18 10NE 17	0.000
9F 19		1.000
10NE 20		0.500
9F 20		0.000
11NA 21	11NA 20	0.000
10NE 21		0.250
9F 21	9F 22	0.000
11NA 22		0.000
10NE 22	10NE 23 10NE 24	0.250
12MG 23	12MG 22	0.000
11NA 23		1.000
12MG 24		0.500
11NA 24		0.000
13AL 25	13AL 24	0.000
12MG 25		0.250
11NA 25	11NA 26	0.000
13AL 26		0.000
12MG 26	12MG 27 12MG 28	0.250
14SI 27	14SI 26	0.000
13AL 27		1.000
14SI 28		1.000
13AL 28		0.000
14SI 29		0.000
13AL 29	13AL 30	0.000
15P 30	15P 28 15P 29	0.000
14SI 30	14SI 31 14SI 32	0.000
15P 31		1.000

Table 2.2 (Cont'd)

16S 32	16S 30	16S 31	1.000
15P 32			0.000
16S 33			0.000
15P 33	15P 34		0.000
17CL 34	17CL 33		0.000
16S 34			0.000
17CL 35			0.500
16S 35	16S 36	16S 37	0.000
18AR 36	18AR 34	18AR 35	0.500
17CL 36			0.000
18AR 37			0.000
17CL 37	17CL 38	17CL 39	0.500
19K 38	19K 37		0.000
18AR 38			0.500
19K 39			0.250
18AR 39			0.000
20CA 40	20CA 39		0.500
19K 40			0.250
18AR 40	18AR 41		0.000
20CA 41			0.000
19K 41			0.500
20CA 42			0.250
19K 42	19K 43		0.000
21SC 43	21SC 42		0.000
20CA 43			0.000
21SC 44			0.000
20CA 44	20CA 45	20CA 46	0.250
22TI 45	23V 45	22TI 44	0.000
21SC 45			1.000
22TI 46			0.500
21SC 46			0.000
22TI 47			0.250
21SC 47	21SC 48		0.000
23V 48	23V 46	23V 47	0.000
22TI 48			0.250
23V 49			0.250
22TI 49	22TI 50		0.000
24CR 50	24CR 48	24CR 49	0.000
23V 50			0.250
24CR 51			0.000
23V 51	23V 52	23V 53	0.500
25MN 52	25MN 51		0.000
24CR 52			0.500
26FE 53			0.000
25MN 53			0.250
24CR 53			0.250
26FE 54			0.000
25MN 54			0.250
24CR 54			0.250
26FE 55			0.000
25MN 55			0.500
26FE 56			1.000

When the projectile is hydrogen the cross section

$$\sigma = 44.9\ A^{0.7} \tag{2.3-2}$$

(Letaw et al., 1983a) has been used.

Significant unknowns in the cross section data base are cross sections for production of light products (A < 6). These cross sections are not known even for proton-nucleus collisions. Errors of 20 percent or more in the proton and He abundances may result from ignoring the production of these nuclides in fragmentation reactions. Rough estimates of these cross sections for production of light nuclei were made based on data obtained by Freier and Waddington (1975).

We note here that uncertainties in the total cross sections are the single greatest uncertainty in these calculations. The error (~ 10 percent) in the total cross section for iron fragmentation causes at least n times that error in the flux after n mean free paths (1 mean free path = 16 gm/cm^2). The error in partial cross sections, when averaged over the isotopes is similar in magnitude to that of the total cross sections.

We have neglected the variation of cross sections with energy in this computation and used the high-energy values. This does not result in significant error because the mean-free-path for fragmentation at low energies is much smaller than the range.

2.4 Ionization Loss

Loss of energy in the atmosphere due to ionization of air molecules is represented by the stopping power of the nuclide. The stopping power

$$W = -\frac{dE}{dx} \tag{2.4-1}$$

is the rate of energy loss [MeV/(g/cm^2)] of material traversed. For protons the stopping power in air varies from roughly 200 MeV/(g/cm^2) at 1 MeV down to about 2 MeV/(g/cm^2) at high energies. For other particles it scales as Z^2. Table 2.3 contains stopping powers of H, He, C, O, Ar, and Fe in air. This table was produced by programs discussed in Adams, et al. (1983a).

The range of particles in air is also required in this work. Range is defined by the integral:

$$\int_0^E \frac{dE}{W_i(E)} \tag{2.4-2}$$

and is calculated in g/cm^2. Table 2.4 contains ranges of H, He, C, O, Ar and Fe in air. Ranges for other nuclides may be interpolated from this table.

Table 2.3

Stopping Power in Air (MeV/(gm/cm^2))

MeV/u	H	He	C	O	Ar	Fe
1.0	2.205E+02	8.433E+02	5.514E+03	8.479E+03	2.378E+04	3.472E+04
1.2	1.951E+02	7.502E+02	5.159E+03	8.034E+03	2.343E+04	3.484E+04
1.5	1.673E+02	6.501E+02	4.703E+03	7.437E+03	2.277E+04	3.461E+04
2.0	1.363E+02	5.394E+02	4.103E+03	6.610E+03	2.154E+04	3.372E+04
2.5	1.157E+02	4.652E+02	3.641E+03	5.950E+03	2.032E+04	3.256E+04
3.0	1.008E+02	4.108E+02	3.275E+03	5.411E+03	1.919E+04	3.134E+04
4.0	8.046E+01	3.348E+02	2.727E+03	4.584E+03	1.723E+04	2.900E+04
5.0	6.850E+01	2.885E+02	2.361E+03	4.013E+03	1.567E+04	2.695E+04
6.0	5.935E+01	2.524E+02	2.074E+03	3.559E+03	1.436E+04	2.513E+04
7.0	5.252E+01	2.249E+02	1.851E+03	3.200E+03	1.325E+04	2.355E+04
8.0	4.721E+01	2.031E+02	1.673E+03	2.908E+03	1.232E+04	2.215E+04
10.0	3.948E+01	1.703E+02	1.406E+03	2.464E+03	1.081E+04	1.982E+04
12.0	3.411E+01	1.465E+02	1.218E+03	2.142E+03	9.647E+03	1.796E+04
15.0	2.856E+01	1.206E+02	1.020E+03	1.799E+03	8.330E+03	1.577E+04
20.0	2.277E+01	9.301E+01	8.130E+02	1.436E+03	6.813E+03	1.317E+04
25.0	1.908E+01	7.659E+01	6.833E+02	1.208E+03	5.799E+03	1.135E+04
30.0	1.647E+01	6.594E+01	5.921E+02	1.049E+03	5.081E+03	1.003E+04
40.0	1.308E+01	5.233E+01	4.707E+02	8.356E+02	4.123E+03	8.249E+03
50.0	1.095E+01	4.382E+01	3.944E+02	7.005E+02	3.490E+03	7.077E+03
60.0	9.486E+00	3.796E+01	3.418E+02	6.073E+02	3.041E+03	6.218E+03
70.0	8.416E+00	3.368E+01	3.033E+02	5.391E+02	2.708E+03	5.564E+03
80.0	7.597E+00	3.040E+01	2.738E+02	4.868E+02	2.450E+03	5.053E+03
100.0	6.424E+00	2.571E+01	2.316E+02	4.119E+02	2.079E+03	4.307E+03
120.0	5.622E+00	2.250E+01	2.028E+02	3.606E+02	1.824E+03	3.789E+03
150.0	4.804E+00	1.923E+01	1.733E+02	3.083E+02	1.562E+03	3.254E+03
200.0	3.967E+00	1.588E+01	1.432E+02	2.547E+02	1.293E+03	2.700E+03
250.0	3.456E+00	1.383E+01	1.247E+02	2.220E+02	1.128E+03	2.359E+03
300.0	3.113E+00	1.246E+01	1.124E+02	2.000E+02	1.017E+03	2.129E+03
400.0	2.684E+00	1.074E+01	9.692E+01	1.725E+02	8.781E+02	1.840E+03
500.0	2.430E+00	9.726E+00	8.777E+01	1.562E+02	7.958E+02	1.668E+03
600.0	2.265E+00	9.067E+00	8.182E+01	1.457E+02	7.422E+02	1.557E+03
700.0	2.152E+00	8.612E+00	7.773E+01	1.384E+02	7.053E+02	1.480E+03
800.0	2.070E+00	8.286E+00	7.479E+01	1.331E+02	6.788E+02	1.424E+03
1000.0	1.965E+00	7.864E+00	7.098E+01	1.264E+02	6.444E+02	1.353E+03
1200.0	1.903E+00	7.618E+00	6.876E+01	1.224E+02	6.243E+02	1.311E+03
1500.0	1.853E+00	7.419E+00	6.697E+01	1.192E+02	6.081E+02	1.277E+03
2000.0	1.824E+00	7.301E+00	6.590E+01	1.173E+02	5.984E+02	1.256E+03
2500.0	1.823E+00	7.297E+00	6.586E+01	1.172E+02	5.979E+02	1.255E+03
3000.0	1.833E+00	7.339E+00	6.623E+01	1.179E+02	6.013E+02	1.262E+03
4000.0	1.867E+00	7.472E+00	6.743E+01	1.200E+02	6.120E+02	1.285E+03
5000.0	1.904E+00	7.620E+00	6.877E+01	1.224E+02	6.240E+02	1.310E+03
6000.0	1.940E+00	7.764E+00	7.006E+01	1.247E+02	6.356E+02	1.334E+03
7000.0	1.973E+00	7.898E+00	7.127E+01	1.269E+02	6.465E+02	1.357E+03
8000.0	2.004E+00	8.072E+00	7.238E+01	1.288E+02	6.565E+02	1.378E+03

Table 2.4

Range in Air (gm/cm^2)

MeV/u	H	He	C	O	Ar	Fe
1.000	2.907E-03	3.360E-03	2.130E-03	1.972E-03	2.124E-03	2.204E-03
1.200	3.881E-03	4.369E-03	2.581E-03	2.360E-03	2.462E-03	2.525E-03
1.500	5.561E-03	6.095E-03	3.313E-03	2.981E-03	2.981E-03	3.007E-03
2.000	8.919E-03	9.493E-03	4.684E-03	4.124E-03	3.882E-03	3.824E-03
2.500	1.295E-02	1.350E-02	6.241E-03	5.401E-03	4.837E-03	4.666E-03
3.000	1.762E-02	1.809E-02	7.982E-03	6.813E-03	5.849E-03	5.540E-03
4.000	2.890E-02	2.896E-02	1.202E-02	1.004E-02	8.049E-03	7.393E-03
5.000	4.254E-02	4.188E-02	1.677E-02	1.378E-02	1.048E-02	9.392E-03
6.000	5.838E-02	5.675E-02	2.220E-02	1.802E-02	1.315E-02	1.154E-02
7.000	7.648E-02	7.357E-02	2.835E-02	2.277E-02	1.605E-02	1.384E-02
8.000	9.675E-02	9.233E-02	3.518E-02	2.802E-02	1.918E-02	1.628E-02
10.000	1.437E-01	1.355E-01	5.091E-02	4.002E-02	2.612E-02	2.162E-02
12.000	1.988E-01	1.864E-01	6.932E-02	5.398E-02	3.395E-02	2.755E-02
15.000	2.961E-01	2.771E-01	1.018E-01	7.854E-02	4.736E-02	3.753E-02
20.000	4.953E-01	4.677E-01	1.683E-01	1.287E-01	7.402E-02	5.700E-02
25.000	7.382E-01	7.063E-01	2.492E-01	1.897E-01	1.059E-01	7.991E-02
30.000	1.023E+00	9.889E-01	3.439E-01	2.610E-01	1.428E-01	1.061E-01
40.000	1.716E+00	1.676E+00	5.731E-01	4.331E-01	2.307E-01	1.679E-01
50.000	2.562E+00	2.516E+00	8.532E-01	6.432E-01	3.364E-01	2.413E-01
60.000	3.554E+00	3.500E+00	1.181E+00	8.893E-01	4.594E-01	3.256E-01
70.000	4.685E+00	4.622E+00	1.555E+00	1.170E+00	5.989E-01	4.208E-01
80.000	5.948E+00	5.875E+00	1.973E+00	1.482E+00	7.542E-01	5.263E-01
100.000	8.847E+00	8.752E+00	2.931E+00	2.200E+00	1.110E+00	7.667E-01
120.000	1.221E+01	1.209E+01	4.043E+00	3.033E+00	1.521E+00	1.044E+00
150.000	1.806E+01	1.789E+01	5.974E+00	4.479E+00	2.234E+00	1.523E+00
200.000	2.969E+01	2.943E+01	9.814E+00	7.355E+00	3.650E+00	2.472E+00
250.000	4.336E+01	4.299E+01	1.433E+01	1.073E+01	5.311E+00	3.583E+00
300.000	5.877E+01	5.828E+01	1.941E+01	1.454E+01	7.180E+00	4.832E+00
400.000	9.386E+01	9.310E+01	3.099E+01	2.321E+01	1.143E+01	7.672E+00
500.000	1.335E+02	1.324E+02	4.406E+01	3.299E+01	1.623E+01	1.087E+01
600.000	1.765E+02	1.751E+02	5.827E+01	4.362E+01	2.144E+01	1.434E+01
700.000	2.223E+02	2.205E+02	7.335E+01	5.490E+01	2.697E+01	1.803E+01
800.000	2.701E+02	2.679E+02	8.912E+01	6.670E+01	3.275E+01	2.188E+01
1000.000	3.703E+02	3.673E+02	1.222E+02	9.143E+01	4.486E+01	2.994E+01
1200.000	4.747E+02	4.709E+02	1.566E+02	1.172E+02	5.747E+01	3.834E+01
1500.000	6.360E+02	6.309E+02	2.098E+02	1.570E+02	7.695E+01	5.131E+01
2000.000	9.107E+02	9.034E+02	3.004E+02	2.248E+02	1.101E+02	7.341E+01
2500.000	1.187E+03	1.178E+03	3.916E+02	2.930E+02	1.436E+02	9.566E+01
3000.000	1.463E+03	1.451E+03	4.826E+02	3.611E+02	1.769E+02	1.179E+02
4000.000	2.008E+03	1.992E+03	6.624E+02	4.956E+02	2.428E+02	1.617E+02
5000.000	2.543E+03	2.523E+03	8.388E+02	6.276E+02	3.074E+02	2.048E+02
6000.000	3.067E+03	3.043E+03	1.012E+03	7.571E+02	3.708E+02	2.470E+02
7000.000	3.583E+03	3.554E+03	1.182E+03	8.843E+02	4.331E+02	2.885E+02
8000.000	4.089E+03	4.056E+03	1.349E+03	1.009E+03	4.944E+02	3.293E+02

2.5 Flux at the Top of the Atmosphere

The cosmic ray flux at the top of the atmosphere has been measured extensively. A compilation of these results and procedures for estimating the fluxes are given in Adams et al. (1981). These fluxes are dependent upon various solar system and near-earth environmental factors. Among these the 11-year solar cycle causes variations of up to an order of magnitude in fluxes. They are greatest at solar minimum, the most recent of which was late in 1977. Solar flares, which are of short duration and occur at unpredictable intervals, can cause increases of many orders of magnitude in the low energy flux. The magnetic field of the earth however can deflect all low energy charged particles below some cutoff which can be as high as 8 GeV/nucleon ($A/Z = 2$) and averages 1 or 2 GeV/nucleon.

The cosmic ray fluxes have errors of 30 percent or more. This error contributes to the overall estimate of upset probabilities, and is the most important error at high altitudes.

Isotopic abundances are not critical in estimating soft upset rates. They were taken from current data as mentioned in Section 2.2.

2. 6 Results of Propagation

Vertical flux of several groups of cosmic rays as computed by the methods of this section are shown in Figure 2.2. They are compared with data of Webber et al. (1967). Good agreement with these data is found.

3.0 Cosmic Ray Fluxes in the Atmosphere

3.1 Integrated Flux in the Atmosphere

In this section the combination of differential energy fluxes into a total particle flux at any point in the atmosphere is discussed. The particle flux at any point is both zenith and azimuthal angle dependent. The two factors which determine the flux in any direction are geomagnetic cutoff and pathlength. The zenith angle, θ, is the angle the cosmic ray trajectory makes with the vertical. Pathlength in the atmosphere depends only on this angle. We may define a function $X(\theta,x_0)$ (see Section 3.2) giving the number of grams to the top of the atmosphere proceeding at a zenith angle θ from a point whose vertical depth in the atmosphere is x_0 g/cm^2. This function has the property:

$$X(0,x_0) = x_0 \qquad (3.1\text{-}1)$$

The geomagnetic cutoff at a point depends both on the zenith and azimuthal angles. We define the azimuthal angle, ϕ, as the incoming direction of the cosmic ray as measured with respect to geomagnetic east. At any geographic point, the cutoff vs. zenith and azimuthal angles is completely determined by the vertical cutoff. Thus, the lower limit of rigidities allowed within the atmosphere at any place is given by a function $R(\theta,\phi,R_V)$ (see Section 3.3). The rigidity is related to energy/nucleon for a particular species i by:

$$R(GV/c) = \frac{A_i}{1000Z_i} \sqrt{E(E + 1863)} \qquad (3.1\text{-}2)$$

where E is expressed in MeV/nucleon.

Given the pathlength and rigidity cutoff functions and the flux vs. energy and pathlength, J(x,E), as computed in Section 2, the total flux at a point is:

$$F_T(x_o,E) = \int_0^{\pi} \sin\theta \, d\theta \int_0^{2\pi} d\phi \; J(X(\theta,x_o),E) \; g(\theta,\phi,E) \qquad (3.1\text{-}3)$$

where J(X,E) is the calculated particle flux (see Section 3) for energy E and pathlength X.

The function $g(\theta,\phi,E) = 1$ if the particle was able to enter the top of the atmosphere and $= 0$ otherwise. We evaluate $g(\theta,\phi,E)$ by comparing the range of the nuclide at energy E in air with the range at cutoff rigidity minus the pathlength. If

$$\text{Range}(E) \gtrsim \text{Range}(E_{cutoff}) - X(\theta, x_o) \qquad (3.1\text{-}4)$$

then the range at the top of the atmosphere was greater than the range at cutoff energy (implying the energy was greater than cutoff energy), and $g(\theta,\phi,E) = 1$.

The flux calculations are performed for a limited number of pathlengths (in this work, 7). The flux at any other pathlength is determined by interpolating between these fluxes (or extrapolating if $X(\theta,x_o) > 100$ g/cm^2. The fluxes at two nearby points x_o and x_1 are J_o and J_1 respectively. Assuming an exponential decrease in flux with pathlength the flux at x g/cm^2 is:

$$J(x) = J_o \quad \exp \left\{ \frac{\ln(J_0/J_1)}{(x_1 - x_o)} \quad (x - x_o) \right\} \qquad (3.1\text{-}5)$$

Figure 3.1 shows total flux levels for the altitudes of interest in this report versus geomagnetic cutoff. From the figure one sees that total flux can be reduced more than a factor ten by the geomagnetic cutoff. Roughly equal spacing of the curves corresponds to the roughly exponential drop in flux with pathlength.

3.2 Zenith Angle Dependence of Atmospheric Depth

The variation of pathlength with zenith angle and altitude is computed in this section. Figure 3.2 shows a schematic diagram of

earth's atmosphere at some altitude h. The vertical distance to the top of the atmosphere is denoted by x. We wish to calculate the distance, y, to the top of the atmosphere at a zenith angle θ. Applying the law of cosines we have:

$$y^2 + 2y(R_e+h)\cos\theta + (R_e+h)^2 = (R_e+h+x)^2 \tag{3.2-1}$$

therefore:

$$y = (R_e+h)\left\{\left[\left(\frac{R_e+h+x}{R_e+h}\right)^2 - \sin^2\theta\right]^{1/2} - \cos\theta\right\} \tag{3.2-2}$$

The square root may be re-expressed as:

$$\cos\theta\left[1 + \frac{2x}{(R_e+h)\cos^2\theta} + \frac{x^2}{(R_e+h)^2\cos^2\theta}\right]^{1/2} \tag{3.2-3}$$

In this work, the altitudes under consideration are less than 64 km whereas the radius of Earth is ~ 6400 km. The third term in brackets may be neglected, while so long as $\theta < 80^o$ the remainder can be expanded to yield

$$y = x\sec\theta \tag{3.2-4}$$

Therefore, for zenith angles which encompass the majority of cosmic rays at a point, the relation between y and x is linear.

The linear relationship between x and y implies a linear relationship between the pathlength along the vertical to the pathlength at θ. In moving vertically between x and x + dx, a density $\rho(x)$ is encountered and a pathlength $\rho(x)dx$ is traversed. The corresponding move at an angle θ is over a distance $dy = dx \sec\theta$ and therefore involves traversal of precisely $\sec\theta$ times the vertical pathlength - independent of x. Thus, the pathlength vs. zenith angle relation is simply

$$X(\theta,x_0) = x_0\sec\theta \tag{3.2-5}$$

At the point where this relation breaks down ($\theta = 80^o$) the cosmic ray flux is negligible, having passed through almost 6 times as much air as the vertical flux.

3.3 Geomagnetic Cutoff

Earth's magnetic field serves as an extremely effective shield of low to medium energy cosmic rays. This shielding action is characterized by a vertical rigidity cutoff at each geographical location (see energy/rigidity relation, eq. 3.1-2). Positively charged particles having rigidities below the cutoff cannot arrive at a point

vertically or from the east because they are deflected away. Arriving from the west they are deflected toward Earth and hence are able to penetrate at lower energies.

Vertical geomagnetic cutoffs have been computed at 20 km altitude by Shea and Smart (1975). For roughly 800 geographical positions, charged particles arriving vertically were propagated backward through a precise model of the geomagnetic field. Such trajectories, when the rigidity is below cutoff, eventually intersect the earth's surface. When the rigidity is above cutoff they escape earth. This method gives an accurate determination of the cutoff rigidity. A contour plot of the vertical cutoff data is presented in Figure 3.3. Note that more than half earth's surface has a cutoff rigidity of greater than 4 GV. Since the average cosmic ray energy is roughly 1 or 2 GeV/nucleon most cosmic rays are deflected from earth by its magnetic field.

The cutoff rigidity in directions other than the vertical depends on the angle of arrival (see Fig. 3.4). Low energy particles arrive predominantly west, while particles with energy much greater than the cutoff arrive from any direction. Exact arrival angles are described by the Stormer cones. The relation between the Stormer cone angle, γ, and cutoff is approximately

$$R = \frac{4R_V}{[1 + (1 - \cos\gamma \cos^3\lambda)^{1/2}]^2} \qquad (3.3\text{-}1)$$

where

$$\cos^4\lambda = \frac{R_V}{17.6}\left(\frac{1 + \text{altitude (km)}}{6371}\right)^2 \qquad (3.3\text{-}2)$$

Plots of the ratio of cutoff to vertical cutoff for various vertical cutoffs and Stormer cone angles are displayed in Fig. 3.4.

The Stormer cone angle, γ, is related to the azimuthal and zenith angles by

$$\cos\gamma = \cos\phi \sin\theta \qquad (3.3\text{-}3)$$

Eq. 3.3-1 through 3.3-3 allow the geomagnetic cutoff for any arriving angle to be determined from the vertical cutoff and altitude. Further discussion of the geomagnetic field effect on cosmic rays is contained in Adams et al. (1983).

4.0 Single Event Upsets

4. 1 LET Spectra

Up to this point we have discussed the calculation of cosmic ray spectra in the atmosphere for each charge species. There is no direct relation between these spectra and single event upsets because the rate of energy deposit by a cosmic ray bears a complicated functional

relation to its total energy. The LET (linear energy transfer) or stopping power of a charged particle is its rate of energy loss in matter. Table 4.1 shows the stopping power in silicon for several elements in MeV/(g/cm^2). It is notable that the stopping power is at a minimum and roughly constant above 1 GeV/nucleon.

The transformation from energy spectrum to LET spectrum is:

$$J(L) = \sum_i J_i(E) \left(\frac{dL}{dE_i}\right)^{-1} \tag{4.1-1}$$

where the sum over species is necessary because the stopping power is charge dependent. The differential LET spectrum represents the energy transfer characteristics of all species in one spectrum. Because L is not a monotonic function of E its derivative can be zero, thus J(L) has singular points corresponding to stopping power minima and maxima for all the elements. These singularities are avoided in numerical applications by using LET and energy bins, and defining the LET spectrum by

$$J(L) = \sum_i J_i\ (E) \quad \frac{\Delta E}{\Delta L} \tag{4.1-2}$$

In our work we have divided the LET interval ($1 \leq L \leq 10^5$ MeV/(g/cm^2)) and the energy interval ($1 \leq E \leq 8$ GeV/nucleon) into 500 bins with special treatment of particles above 8 GeV/nucleon.

In practice it is convenient to use the integral LET spectrum

$$N(L) = \int_L^\infty J(L)\ dL \tag{4.1-3}$$

because it does not fluctuate, but decreases monotonically from L = 0. Integral LET spectra for cosmic rays at various altitudes and geomagnetic cutoffs are shown in Fig. 4.1-4.9. Interpolation allows the spectrum to be found at any altitude between 50 and 150 thousand feet at any location. For example, Fig. 4.10 shows the integral LET spectrum at 10^3 MeV/(g/cm^2) for all altitudes and cutoffs.

Figure 4.1 shows the typical behavior of the LET spectrum as a function of altitude. At 150,000 ft., where very little slowing down has taken place, the geomagnetic field essentially eliminates ions with LET > 2 x 10^3 MeV/(g/cm^2). This occurs because all heavily ionizing (i.e., low energy) Fe are deflected while higher charge species are extremely rare. By 85,000 ft. many high energy Fe ions have slowed down because of ionization loss and the spectrum is appreciable to 10^4 MeV/(g/cm^2).

4.2 Soft Upsets

The relation between soft upsets and the LET spectrum is governed by the critical charge of the device, Q_c, and the geometry of the sensitive volume. An energy deposition in the sensitive volume causes

Table 4.1

Stopping Power in Silicon (MeV/(gm/cm^2))

MeV/u	H	He	C	O	Ar	Fe
1.000	1.759E 02	7.046E 02	4.401E 03	6.768E 03	1.898E 04	2.773E 04
1.200	1.576E 02	6.305E 02	4.168E 03	6.492E 03	1.894E 04	2.816E 04
1.500	1.369E 02	5.466E 02	3.851E 03	6.089E 03	1.865E 04	2.835E 04
2.000	1.133E 02	4.502E 02	3.409E 03	5.493E 03	1.790E 04	2.802E 04
2.500	9.710E 01	3.846E 02	3.056E 03	4.993E 03	1.706E 04	2.733E 04
3.000	8.524E 01	3.366E 02	2.769E 03	4.575E 03	1.623E 04	2.650E 04
4.000	6.873E 01	2.704E 02	2.330E 03	3.916E 03	1.472E 04	2.477E 04
5.000	5.892E 01	2.308E 02	2.032E 03	3.453E 03	1.348E 04	2.319E 04
6.000	5.131E 01	2.006E 02	1.794E 03	3.078E 03	1.242E 04	2.174E 04
7.000	4.558E 01	1.780E 02	1.607E 03	2.779E 03	1.151E 04	2.046E 04
8.000	4.110E 01	1.604E 02	1.457E 03	2.534E 03	1.074E 04	1.931E 04
10.000	3.452E 01	1.347E 02	1.232E 03	2.158E 03	9.473E 03	1.737E 04
12.000	2.992E 01	1.170E 02	1.070E 03	1.883E 03	8.487E 03	1.580E 04
15.000	2.514E 01	9.888E 01	9.000E 02	1.588E 03	7.361E 03	1.393E 04
20.000	2.014E 01	8.006E 01	7.209E 02	1.274E 03	6.051E 03	1.170E 04
25.000	1.695E 01	6.775E 01	6.082E 02	1.076E 03	5.169E 03	1.012E 04
30.000	1.469E 01	5.880E 01	5.287E 02	9.370E 02	4.542E 03	8.969E 03
40.000	1.172E 01	4.693E 01	4.225E 02	7.502E 02	3.703E 03	7.408E 03
50.000	9.854E 00	3.944E 01	3.552E 02	6.310E 02	3.146E 03	6.377E 03
60.000	8.561E 00	3.426E 01	3.087E 02	5.486E 02	2.748E 03	5.618E 03
70.000	7.612E 00	3.046E 01	2.745E 02	4.879E 02	2.452E 03	5.038E 03
80.000	6.883E 00	2.755E 01	2.483E 02	4.414E 02	2.223E 03	4.583E 03
100.000	5.837E 00	2.336E 01	2.106E 02	3.745E 02	1.891E 03	3.918E 03
120.000	5.120E 00	2.049E 01	1.847E 02	3.286E 02	1.663E 03	3.455E 03
150.000	4.385E 00	1.755E 01	1.583E 02	2.816E 02	1.427E 03	2.974E 03
200.000	3.631E 00	1.453E 01	1.311E 02	2.333E 02	1.185E 03	2.475E 03
250.000	3.170E 00	1.269E 01	1.145E 02	2.037E 02	1.036E 03	2.167E 03
300.000	2.860E 00	1.145E 01	1.033E 02	1.838E 02	9.355E 02	1.959E 03
400.000	2.472E 00	9.895E 00	8.930E 01	1.590E 02	8.097E 02	1.697E 03
500.000	2.242E 00	8.976E 00	8.102E 01	1.442E 02	7.351E 02	1.542E 03
600.000	2.094E 00	8.380E 00	7.565E 01	1.347E 02	6.867E 02	1.441E 03
700.000	1.991E 00	7.971E 00	7.195E 01	1.281E 02	6.533E 02	1.371E 03
800.000	1.918E 00	7.677E 00	6.931E 01	1.234E 02	6.294E 02	1.322E 03
1000.000	1.818E 00	7.277E 00	6.569E 01	1.170E 02	5.968E 02	1.253E 03
1200.000	1.758E 00	7.038E 00	6.354E 01	1.131E 02	5.773E 02	1.213E 03
1500.000	1.708E 00	6.837E 00	6.173E 01	1.099E 02	5.609E 02	1.178E 03
2000.000	1.674E 00	6.702E 00	6.051E 01	1.077E 02	5.498E 02	1.155E 03
2500.000	1.667E 00	6.673E 00	6.025E 01	1.073E 02	5.474E 02	1.150E 03
3000.000	1.671E 00	6.689E 00	6.039E 01	1.075E 02	5.487E 02	1.153E 03
4000.000	1.691E 00	6.770E 00	6.111E 01	1.088E 02	5.551E 02	1.166E 03
5000.000	1.716E 00	6.868E 00	6.199E 01	1.104E 02	5.630E 02	1.182E 03
6000.000	1.740E 00	6.965E 00	6.286E 01	1.119E 02	5.709E 02	1.199E 03
7000.000	1.763E 00	7.055E 00	6.368E 01	1.134E 02	5.782E 02	1.214E 03
8000.000	1.784E 00	7.139E 00	6.444E 01	1.147E 02	5.850E 02	1.228E 03

free electron-hole pairs to be created at a rate of 1 pair per 3.6 eV deposition. This charge is then, by definition of the sensitive volume, able to accumulate and cause a change in device state. Device sensitivities are discussed in a number of articles (Pickel and Blandford, 1980; Petersen et al., 1982; Ziegler and Lanford, 1979). The critical charge is a few pC for devices with length scales on the order of 10-20 μm. It varies roughly as the inverse square of the length scale. Radiation hardened devices have a critical charge about twice as large. The total charge freed when ΔE is deposited is

$$Q(pC) = \frac{\Delta E\ (MeV)}{22.5} \tag{4.1-4}$$

Thus the upset rate is the number of particles per unit time which deposit an energy greater than or equal to

$$\Delta E_c = 22.5\ Q_c \tag{4.1-5}$$

Since ions lose energy linearly at a rate equal to their LET (in thin slabs of matter), the upset rate depends only on the LET spectrum and the distribution of chord lengths in the sensitive volume.

The chord length distribution C(p) is a probability density. Assuming the sensitive volume is subject to an isotropic cosmic ray flux, C(p) dp is the probability that a cosmic ray will pass through between p and p + dp of the region. This is a purely geometric quantity which is known exactly for any rectangular parallelepiped (Pickel and Blandford, 1980). The energy deposited by a charged particle over the length p is

$$\Delta E = \rho L p \tag{4.1-6}$$

where ρ is the density of silicon (2.32 g/cm^3). For a chord length p any charged particle with LET greater than

$$L_{min} = \frac{22.5\ Q_c}{\rho p} \tag{4.1-7}$$

causes a device upset. The total number of upsets/sec is therefore

$$U = \bar{A}_p \int_0^\infty N(L_{min})\ C(p)\ dp, \tag{4.1-8}$$

where $\bar{A}_p$ is the mean projected area of the sensitive volume, equal to one quarter the surface area of a rectangular parallelepiped, and C(p) is the chord length distribution. $N(L_{min})$ is given by Equation 4.1-3.

Figures 4.11 through 4.14 show typical upset rates and their variation with parameters of the calculation. In Figure 4.11 the variation with altitude show that upset rates for a sensitive volume 5 x 10 x 10 μm and critical charge between .1 and 1 pC are strongly dependent on atmospheric depth. At the top of the atmosphere the cutoff excludes highly ionizing Fe, while at lower altitudes ionization loss restores the low energy iron flux. At 75,000 ft. the variation with cutoff is shown in Figure 4.12. Highly ionizing Fe are restored from a cutoff of 1 GV, but not at the 4 GV level. The breakdown into element

groups (Figure 4.13) shows that for critical charges above 0.02 pC, the heaviest ions contribute most to soft upsets. Lighter ions are of importance in proportion to their charge. Figure 4.14 shows the variation of several orders of magnitude possible with varying device sensitivity.

5.0 Computer Code

In this section the computer code developed to estimate soft upset rates in the atmosphere is presented. These programs may be classified as follows:

(i) Data Files and Data File Preparation Programs
(ii) Air Propagation Programs
(iii) Post-processing Programs
(iv) Command File Generator

Classes (i) through (iii) are VAX-11 FORTRAN programs and data files. This FORTRAN version is an extension of the standard FORTRAN-77 and the programs may not be compatible with other systems. The structure of this system of programs and data files is shown in Figure 5.1. The Command File Generator is written in the VAX/VMS command language, DCL (Version 3.2). This file generates a command file which associates the programs and data files correctly and requests all required input data. The command file may be submitted for execution when convenient.

5.1 Data Files and Data File Preparation

There are four input data files required for execution of these programs.

1) SILPOW - Stopping powers of H, He, C, O, Ar, and Fe in Si (same as Table IV.1). Format (F8.3,6(3X,1PE9.3)).

2) ASTPOW - Stopping powers of H, He, C, O, Ar and Fe in air (same as Table II.3). Format (F8.3,6(3X,1PE9.3)).

3) ARANGE - Range of H, He, C, O, Ar and Fe in air (same as Table II.4) Format (F8.3,6(3X,1PE9.3)).

4) SOURCE3 - List of Isotopic Species (same as Table II.2), Format (5(I3,A2,I3),F6.3).

In addition, four data file preparation programs create the remaining four files:

5) QAIR3 - List of partial cross sections for production of lighter nuclides from heavier nuclides in collision with air, produced by the program, QAIR, which requires the subroutine YIELDX (IZ, IA, JZ, JA, E, S). YIELDX returns the partial cross section, S, for the process (N_i + p $\rightarrow$ N_j + p + anything) at energy, E (MeV/nucleon).

6) FLUXES - Fluxes at the top of the atmosphere for the isotopic species in SOURCE3. The program FLUX uses Adams et al. (1981) model of cosmic ray fluxes as modified by recent experimental work.

7) RANGIN - Produced by RANGER and contains data on flux loss in passing through .1 gm/cm^2 air.

8) POWIN - Produced by POWER and contains stopping power data on the nuclides in SOURCE3, interpolated from ASTPOW.

The data file preparation programs are listed in Appendices 1 through 9. A subroutine, CUBSPL, which performs cubic spline interpolation is required for execution of RANGER. This subroutine is shown in Appendix 5.

5.2 Air Propagation Programs

The techniques used in the air propagation programs are discussed in Section 2. The procedure is separated into two parts. In the first (APROP) propagation through all but the last gram of air is performed. Only fragmentation for the last gram is performed. In the second (GRAM) the last gram of ionization loss is performed, meanwhile extending the minimum energy from 30 MeV/u to 1 MeV/u. These programs are shown in Appendices 6 and 7.

The two subroutines of APROP (appended to the program) are AIRMAT and ILOSS. AIRMAT constructs the matrix of total and partial cross sections. The partial cross sections are read in from QAIR3 while the total cross sections are calculated using 2.3-1 and 2.3-2. In ILOSS the coefficients in 2.1-7 pertaining to ionization loss are calculated as needed.

5.3 Post-Processing

The three post-processing programs exhibited in Figure 6.1 are found in Appendices 8, 9 and 10. These programs take the results of air propagation and convert them into the quantities of interest in this report.

ATMOS interpolates the seven flux files at 0, 5, 15, 30, 50, 75, and 100 gm/cm^2 and integrates them over zenith and azimuthal angles to get the total integrated flux. These procedures are discussed in Section 3. The functions RANGE and STPOW estimate the range-energy and stopping power relations in air using the Bethe-Bloch theory. These are used in combination with CUTFACT to evaluate the inequality 3.1-4. CUTFACT determines the angular dependence of the geomagnetic cutoff. The subroutine ALTGRM computes the altitude vs. grammage relation of Fig. 2.1. FLUX performs the exponential interpolation (Eq. 3.1-5).

LETINTT performs the conversion from flux to LET spectrum for all species. It calls the cube spline subroutine, CUBSPL. Methods are discussed in Section 5.1.

UPSET converts the LET spectrum into an upset vs. critical charge profile. It depends on geometrical properties of the sensitive region which is assumed to be a rectangular parallelepiped. The function DIFPLD evaluates the analytic form of the differential pathlength distribution.

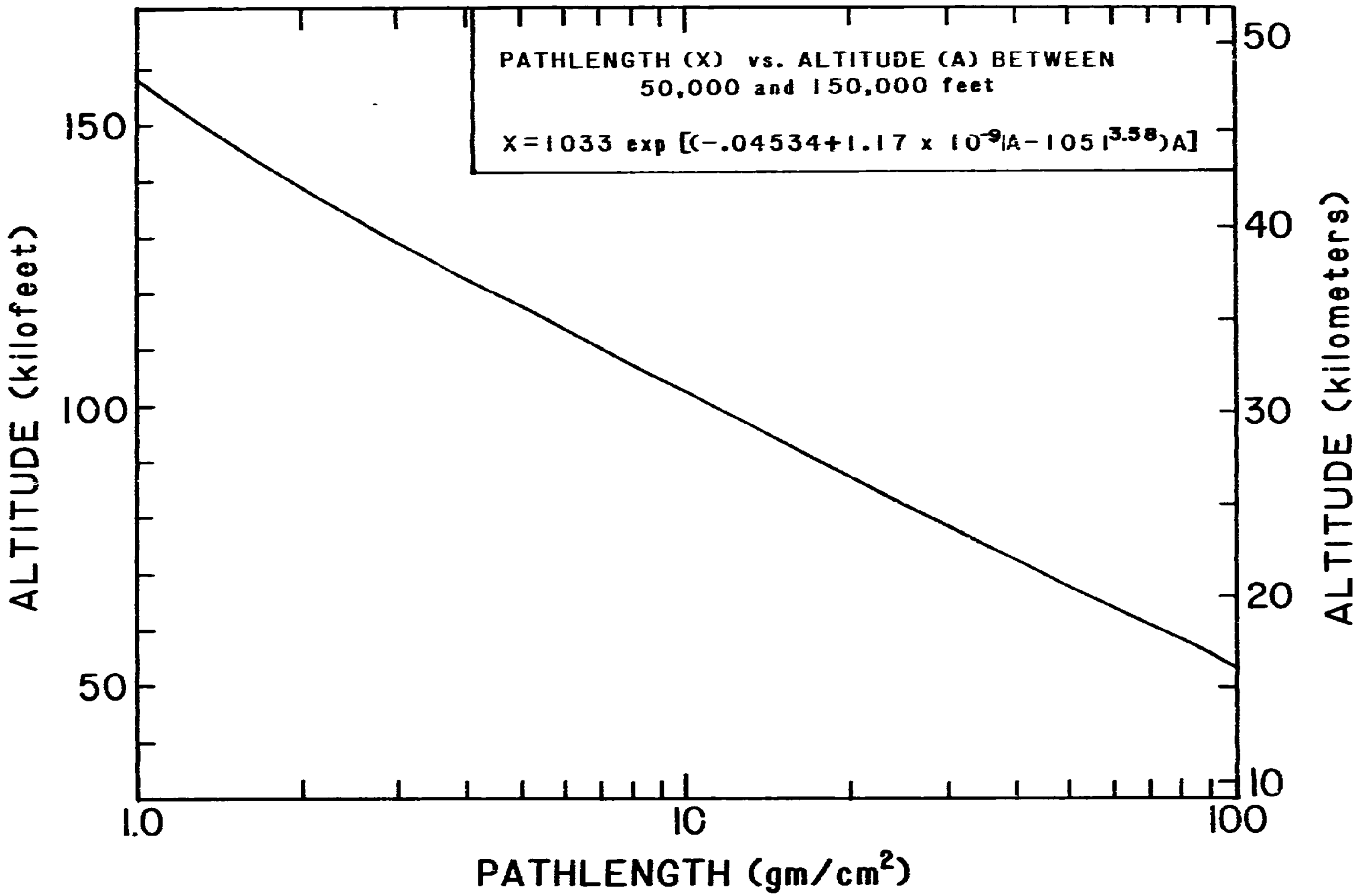

Figure 2.1 Altitude vs. pathlength in the atmosphere between 50,000 ft. and 150,000 ft. Pathlength is proportional to pressure and varies roughly exponentially with altitude.

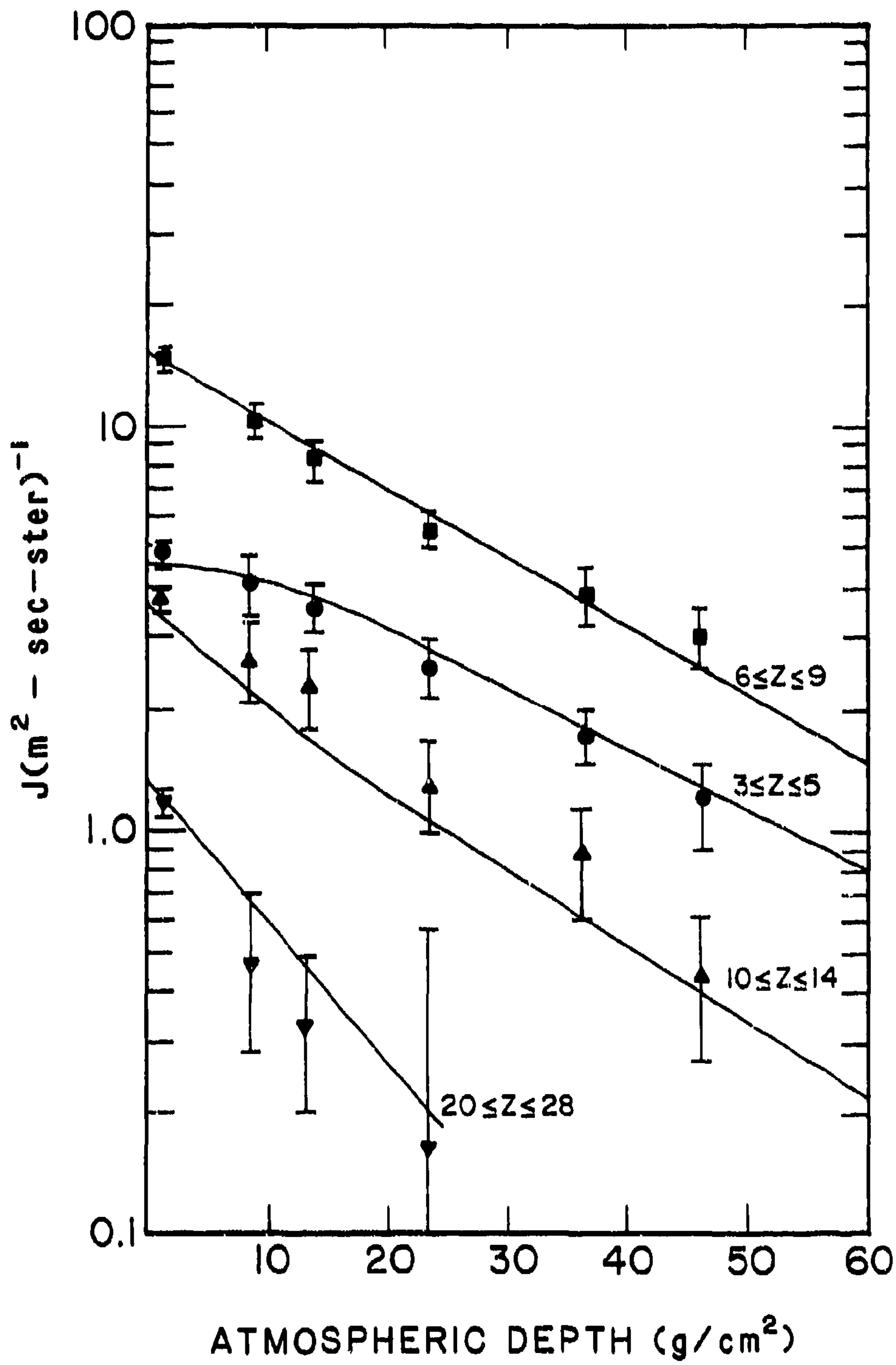

Figure 2.2 Comparison of vertical cosmic ray fluxes in the atmosphere (Webber et al., 1967) with computations of this work.

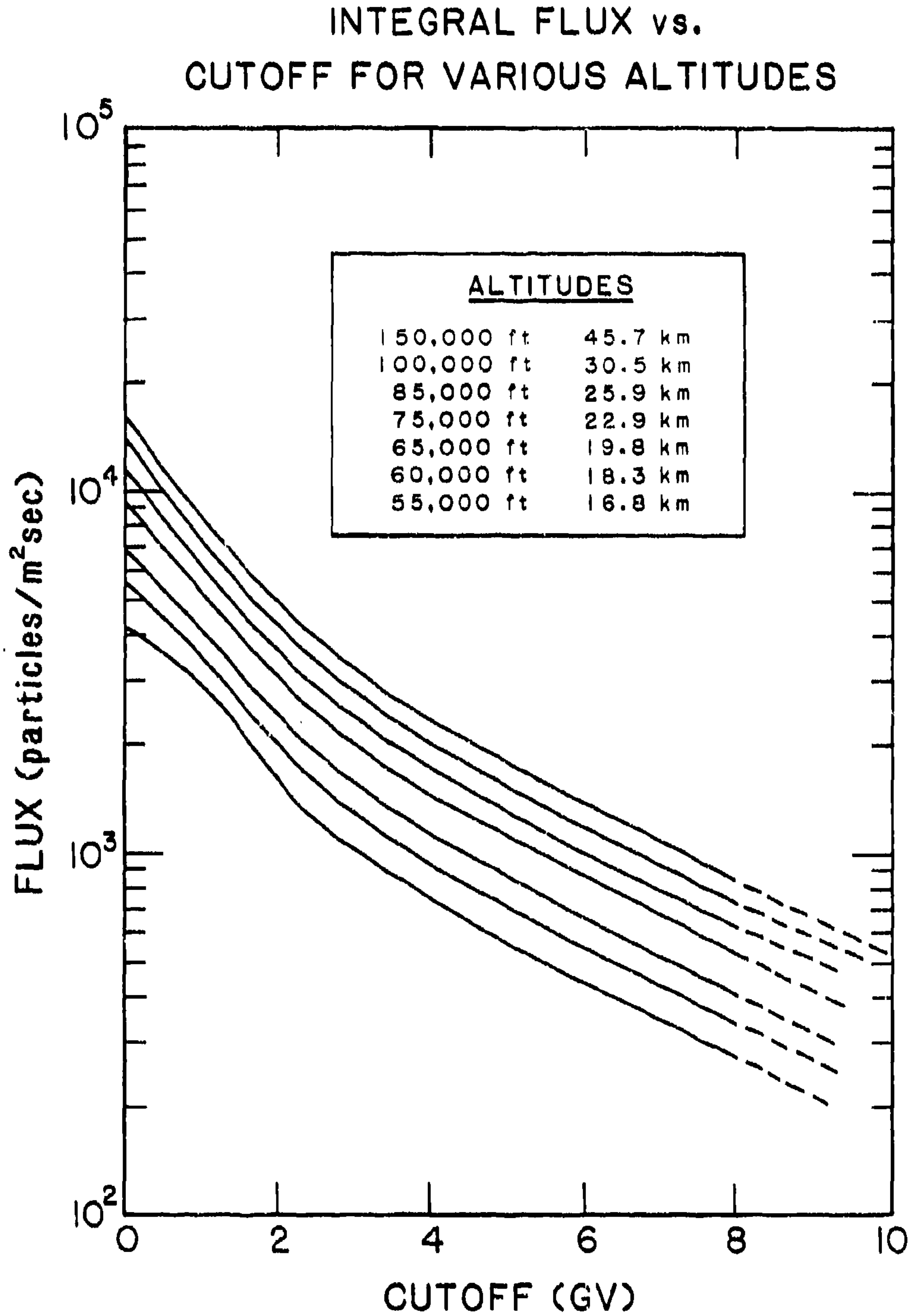

Figure 3.1 Integral cosmic ray flux (mostly protons) as a function of altitude and geomagnetic cutoff. Equal spacing of curves shows roughly exponential decrease with increasing depth in the atmosphere.

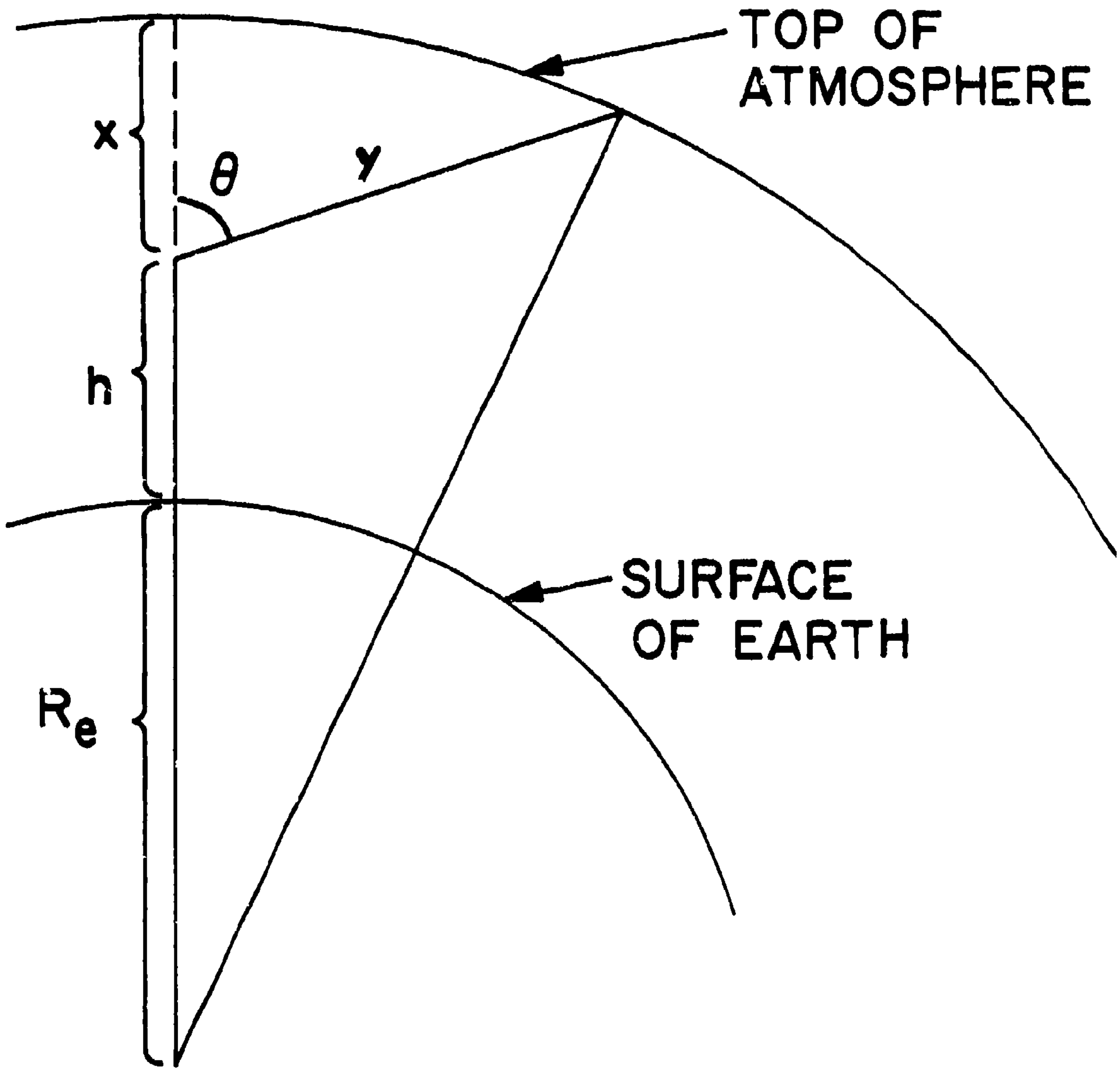

Figure 3.2 Schematic diagram of relation between vertical pathlength, x, to a point in the atmosphere and the pathlength, y, at zenith angle θ.

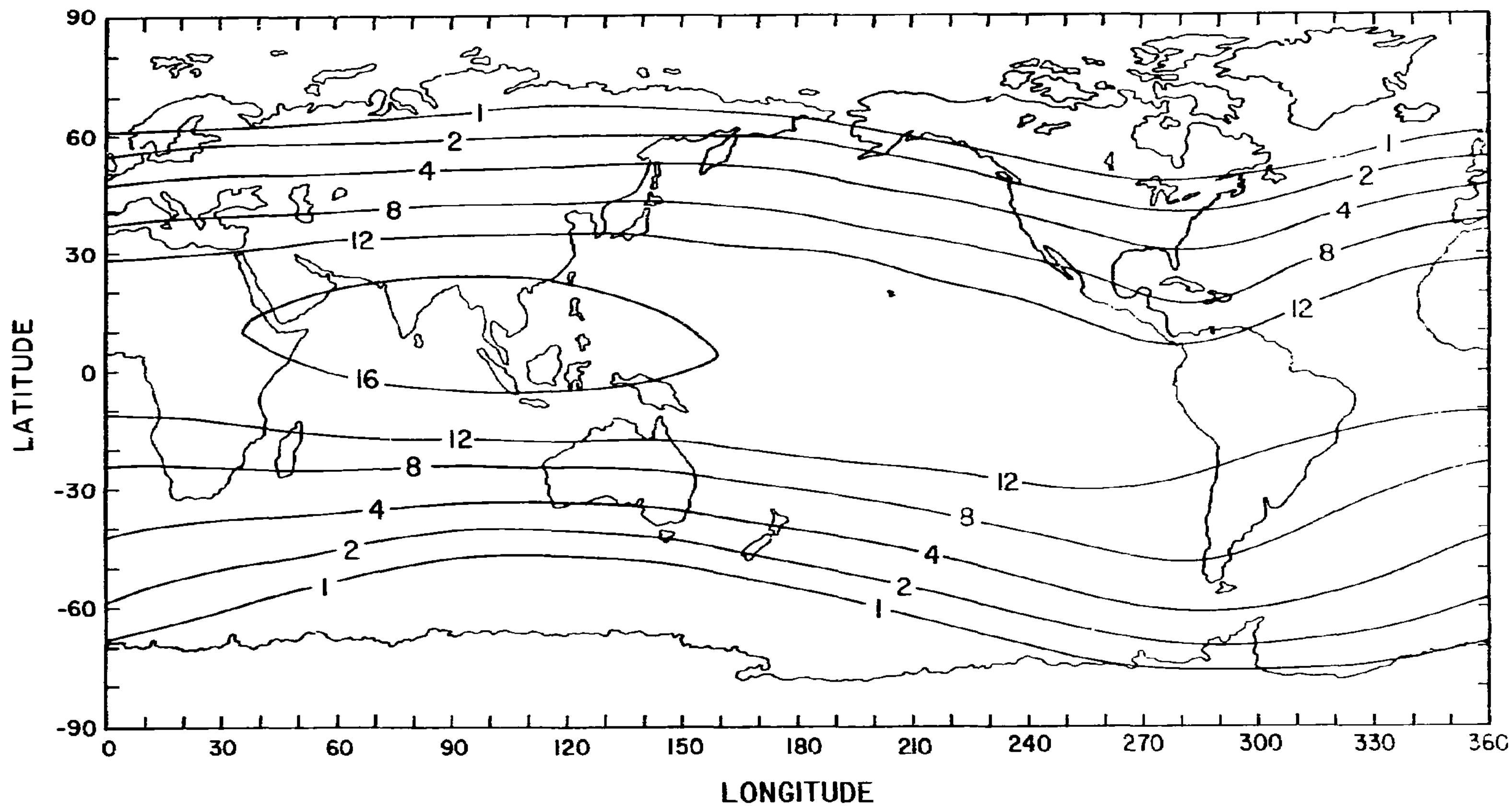

Figure 3.3 Vertical cutoff rigidity at 20 km over earth's surface.

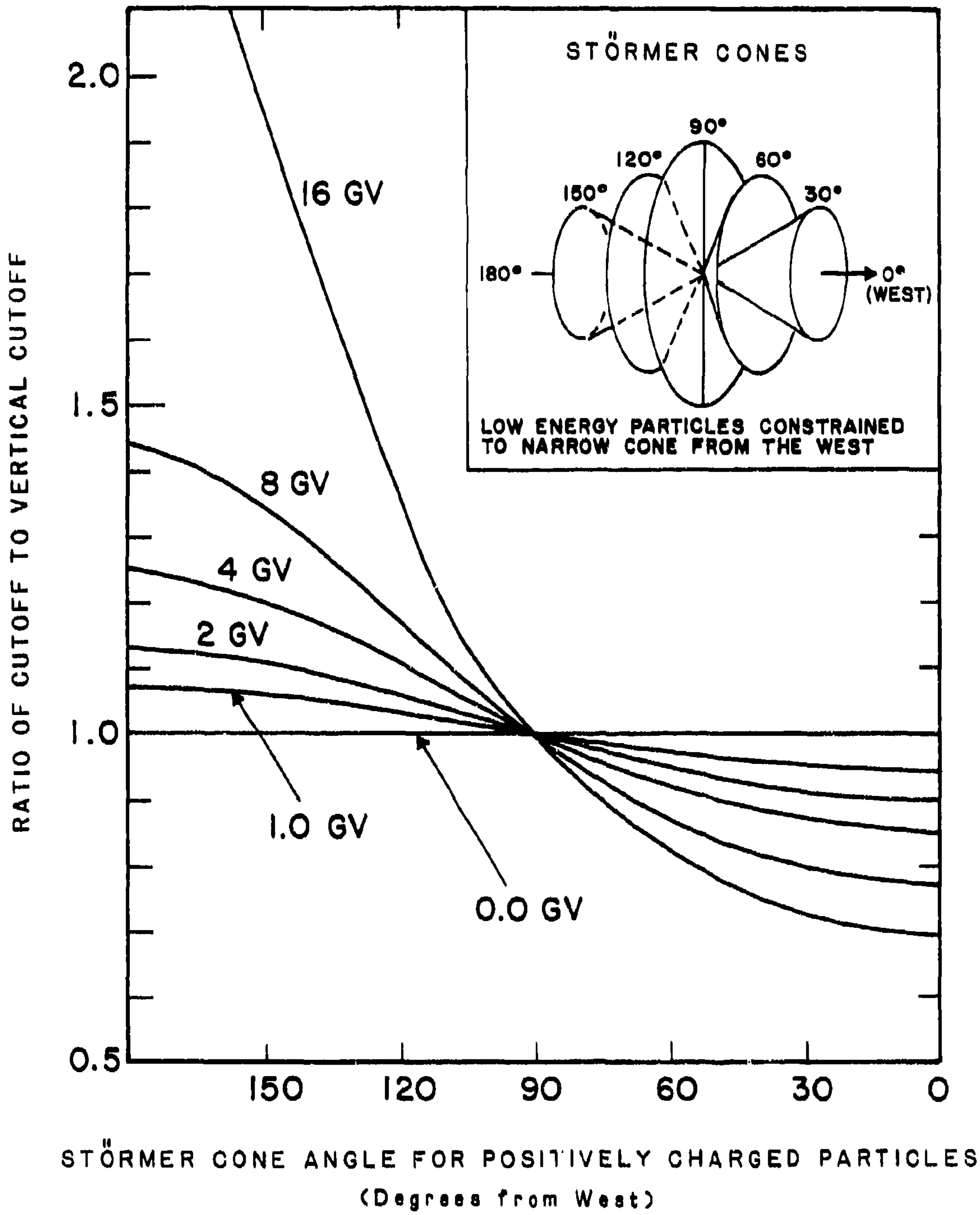

Figure 3.4 Cutoff rigidity vs. Stormer cone angle for various vertical cutoffs. Widest variations in cutoff occur in regions of high vertical cutoff.

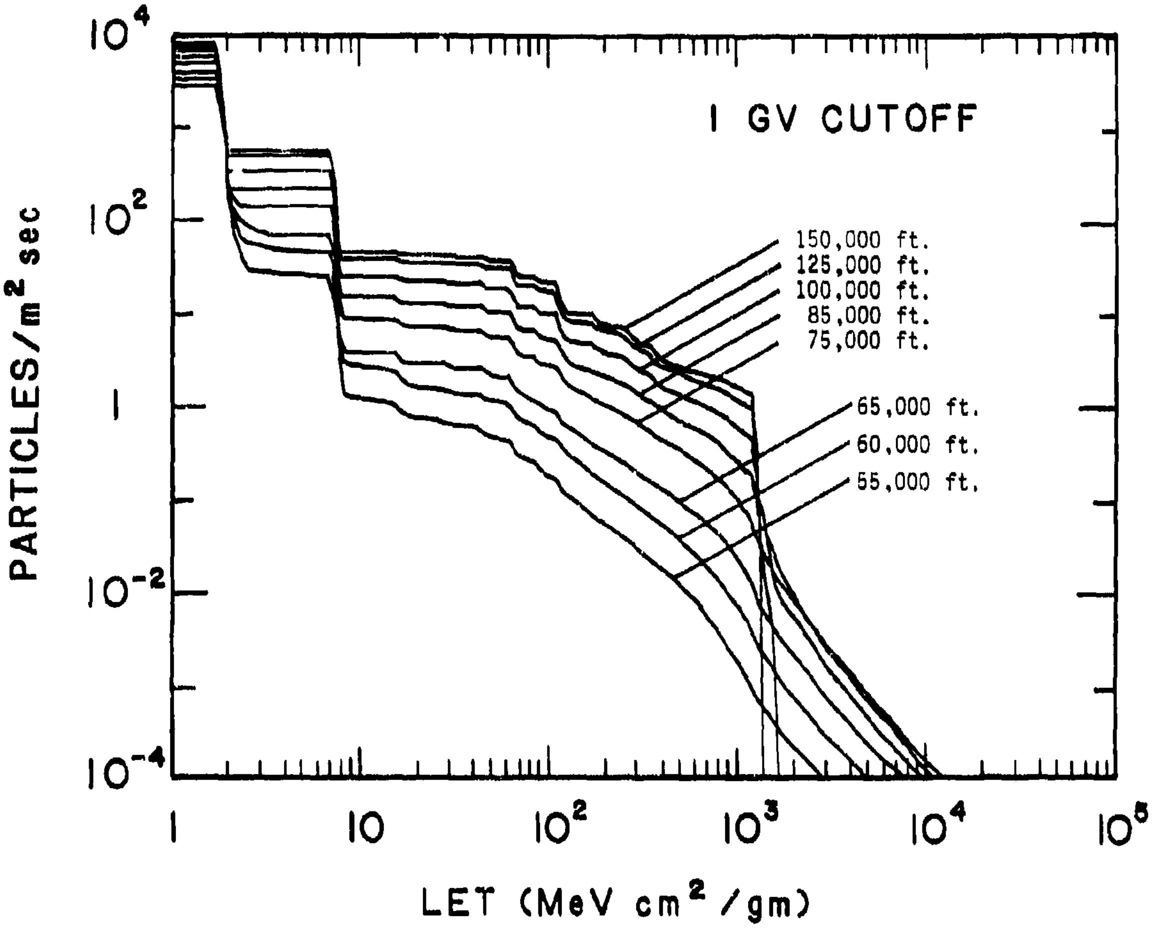

Figure 4.1 LET spectra at 1 GV cutoff for various altitudes.

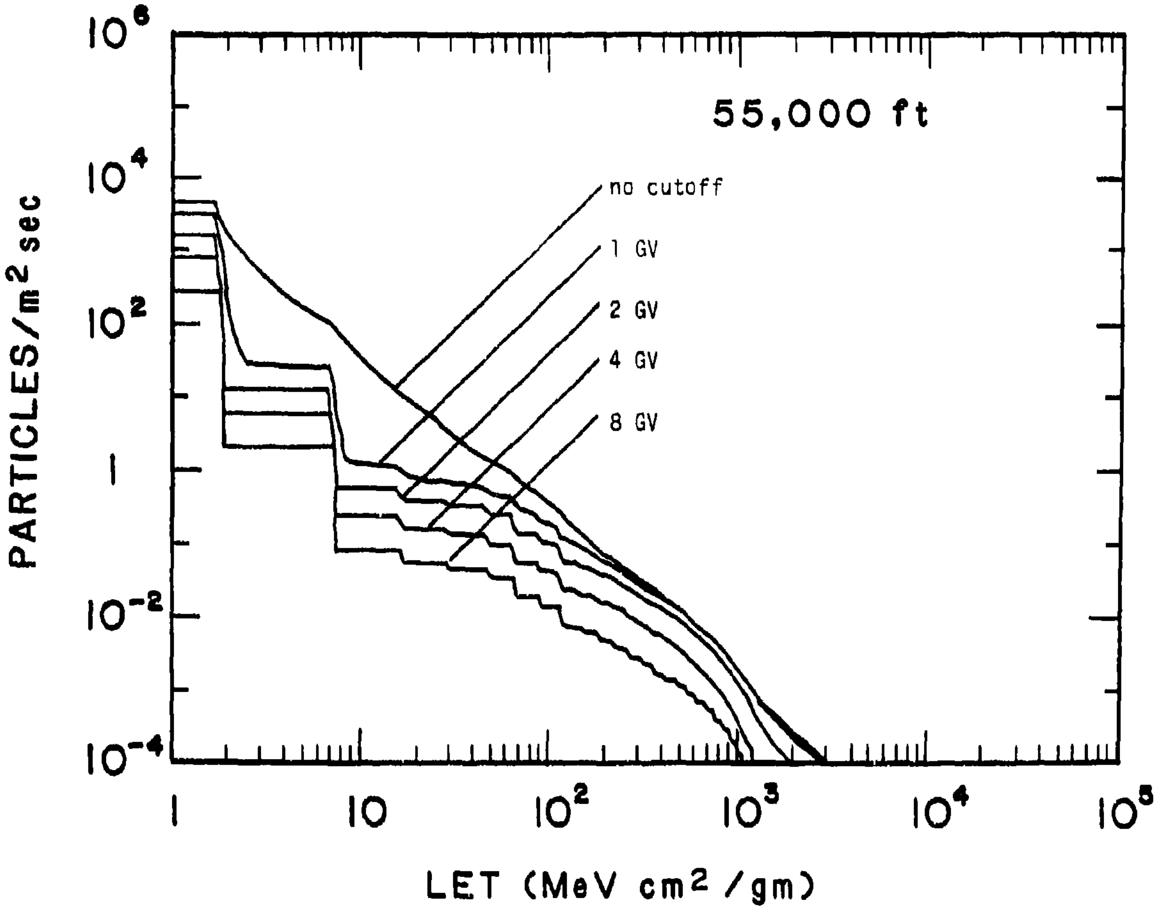

Figure 4.2 LET spectra at 55,000 ft. for several cutoffs.

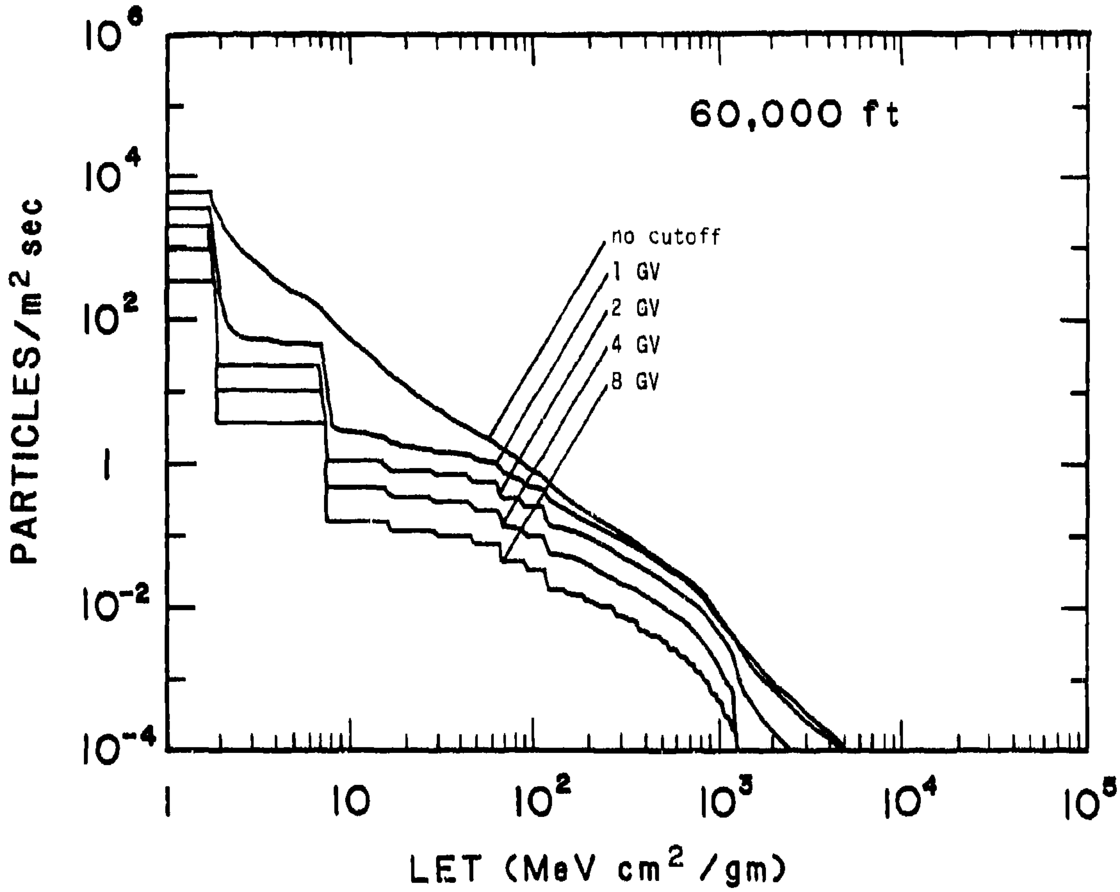

Figure 4.3 LET spectra at 60,000 ft. for several cutoffs.

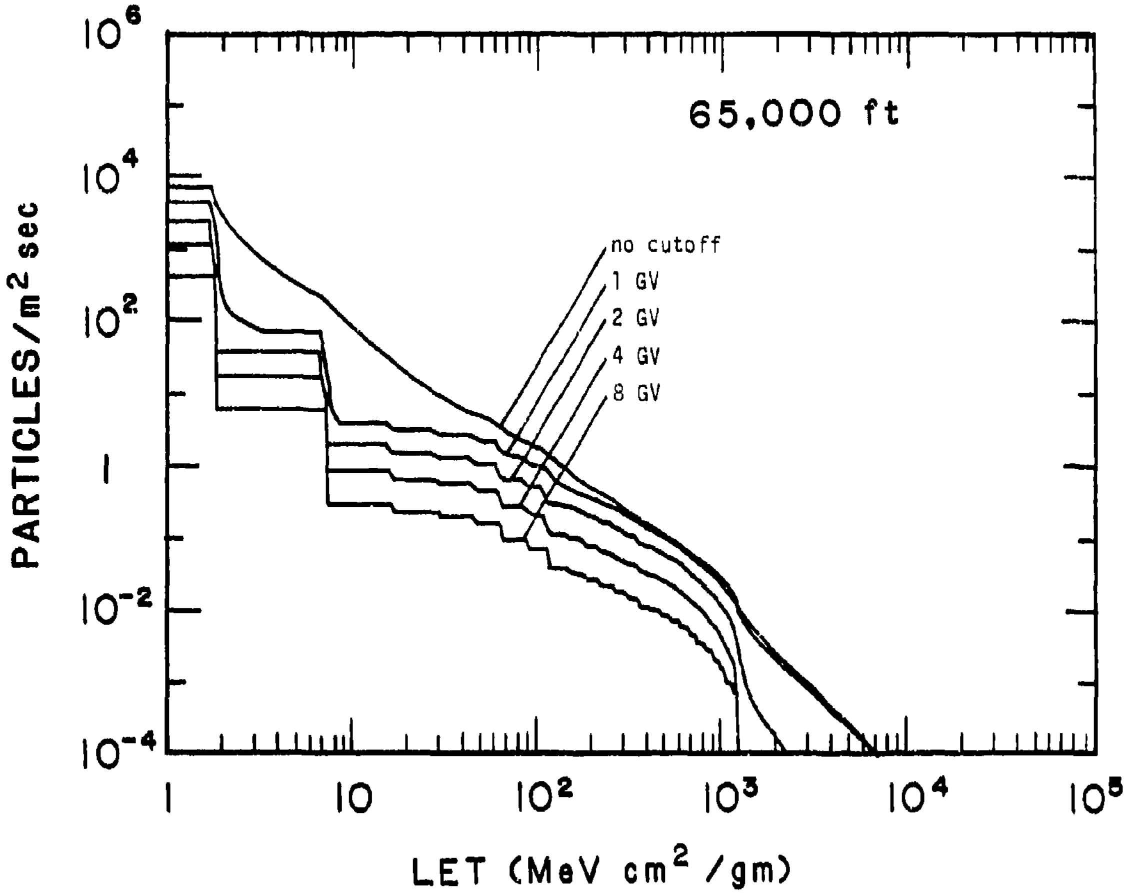

Figure 4.4 LET spectra at 65,000 ft. for several cutoffs.

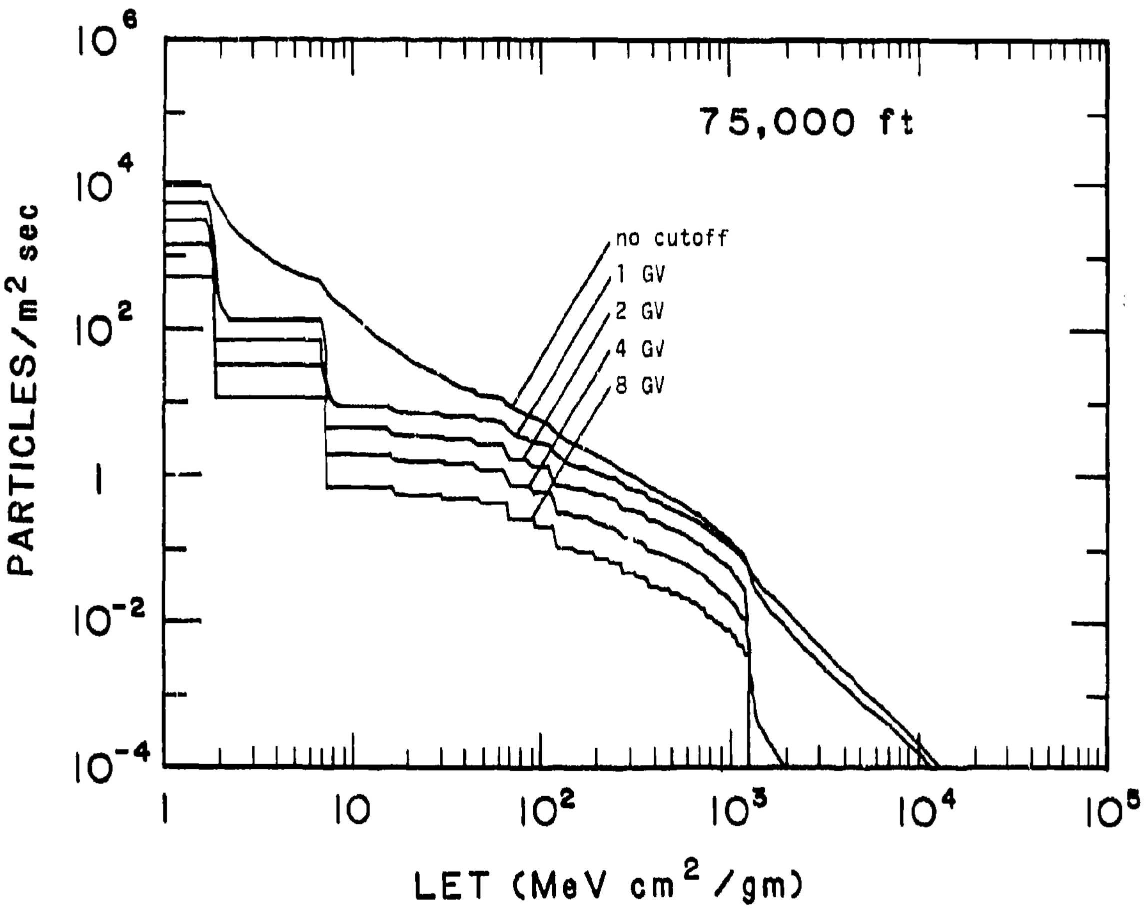

Figure 4.5 LET spectra at 75,000 ft. for several cutoffs.

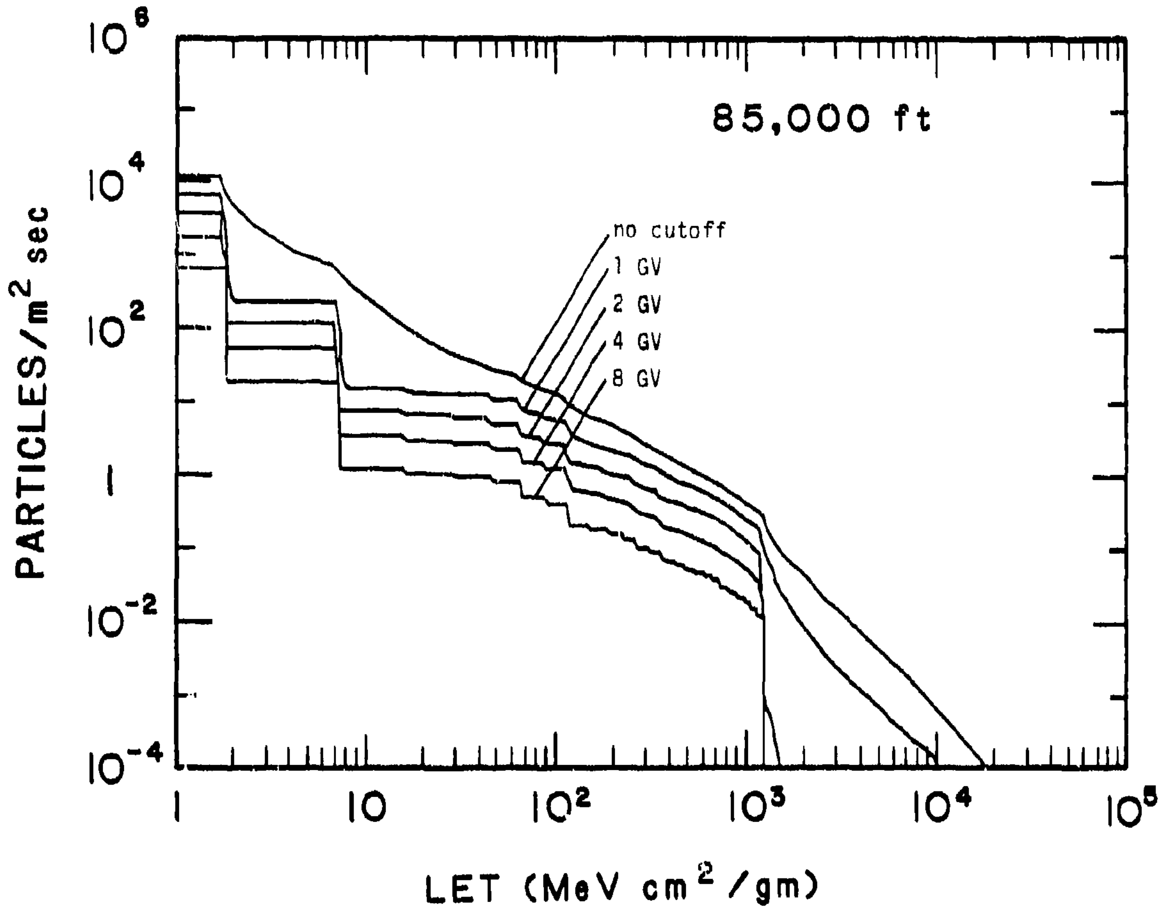

Figure 4.6 LET spectra at 85,000 ft. for several cutoffs.

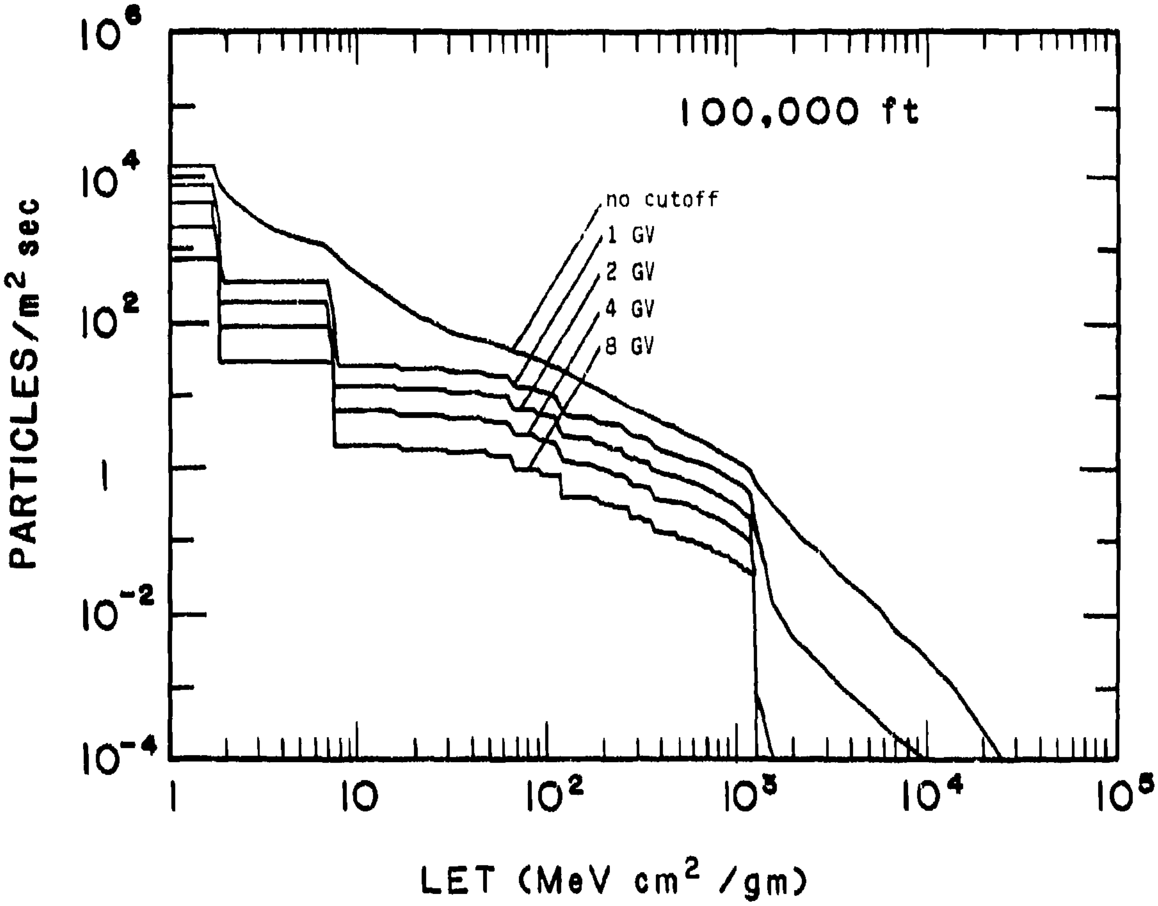

Figure 4.7 LET spectra at 100,000 ft. for several cutoffs.

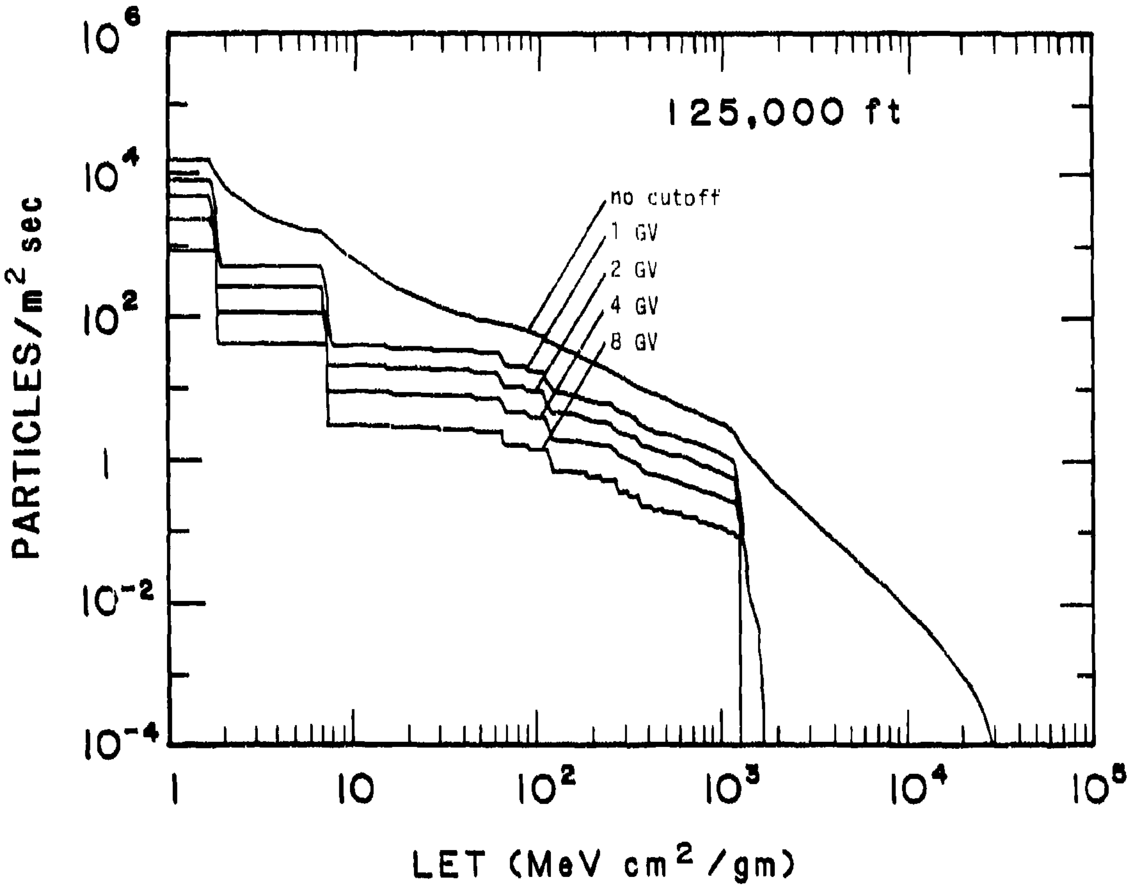

Figure 4.8 LET spectra at 125,000 ft. for several cutoffs.

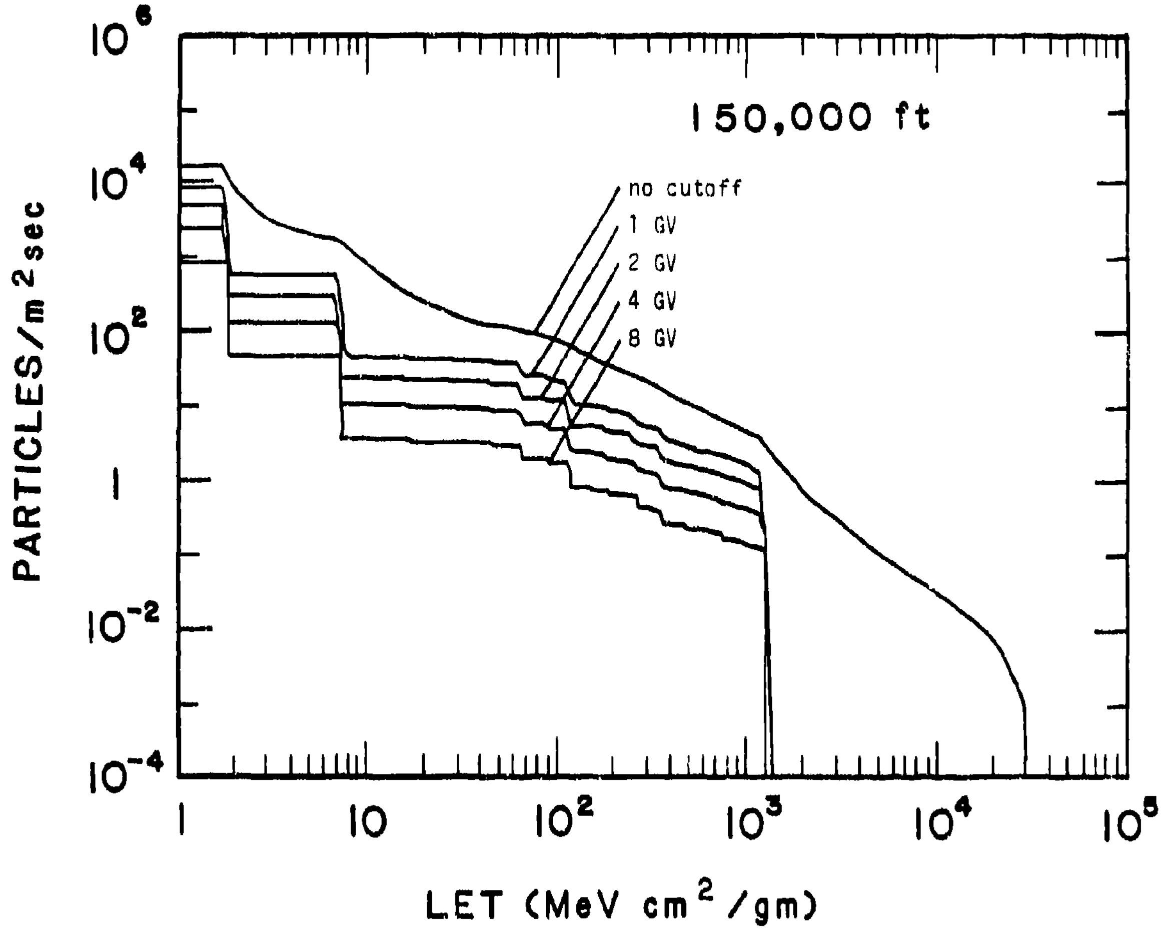

Figure 4.9 LET spectra at 150,000 ft. for several cutoffs.

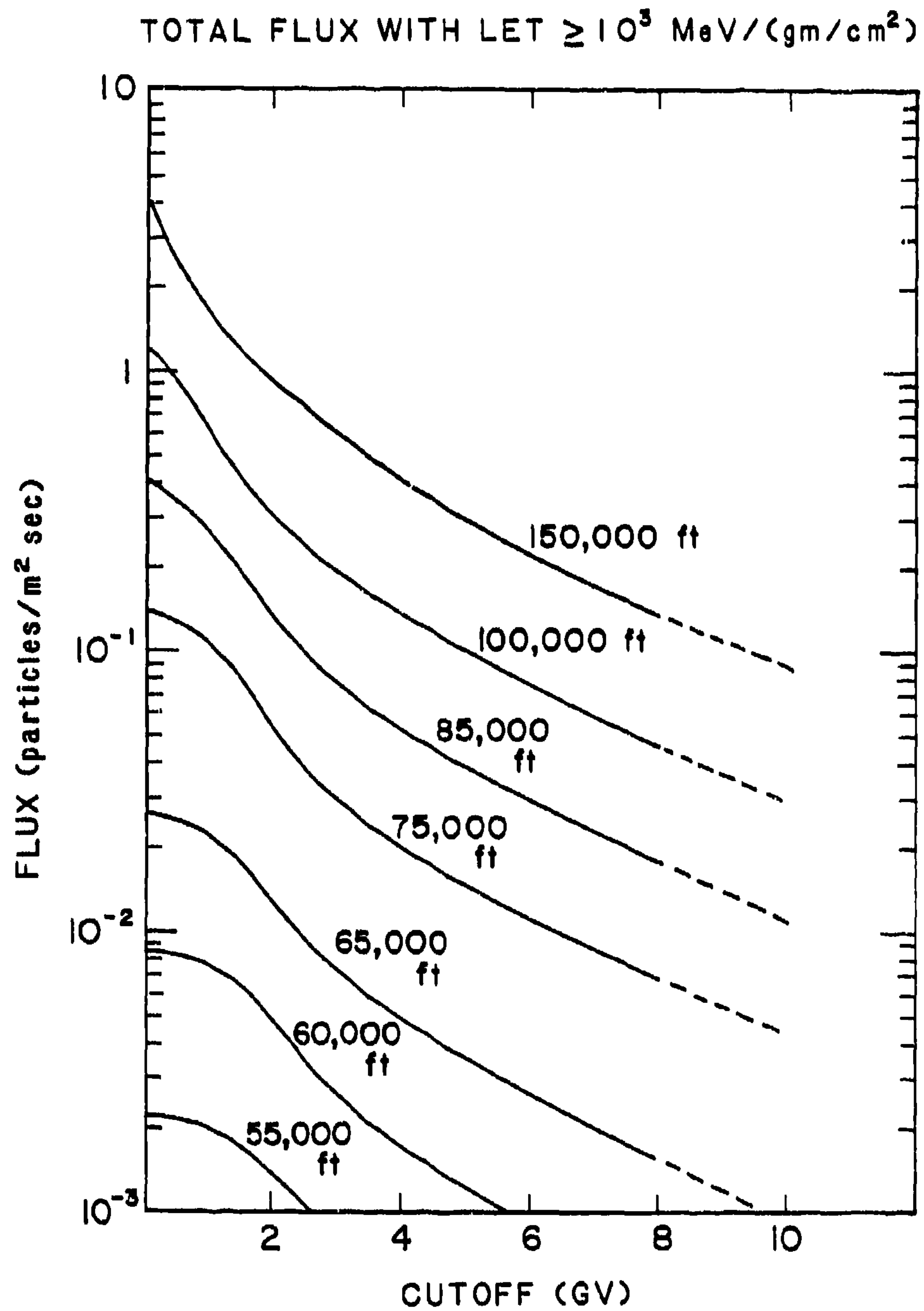

Figure 4.10 Integral flux with LET $\geq 10^3$ MeV/(g/cm^2) as a function of altitude and cutoff. Values were taken from Figures 4.2 - 4.9.

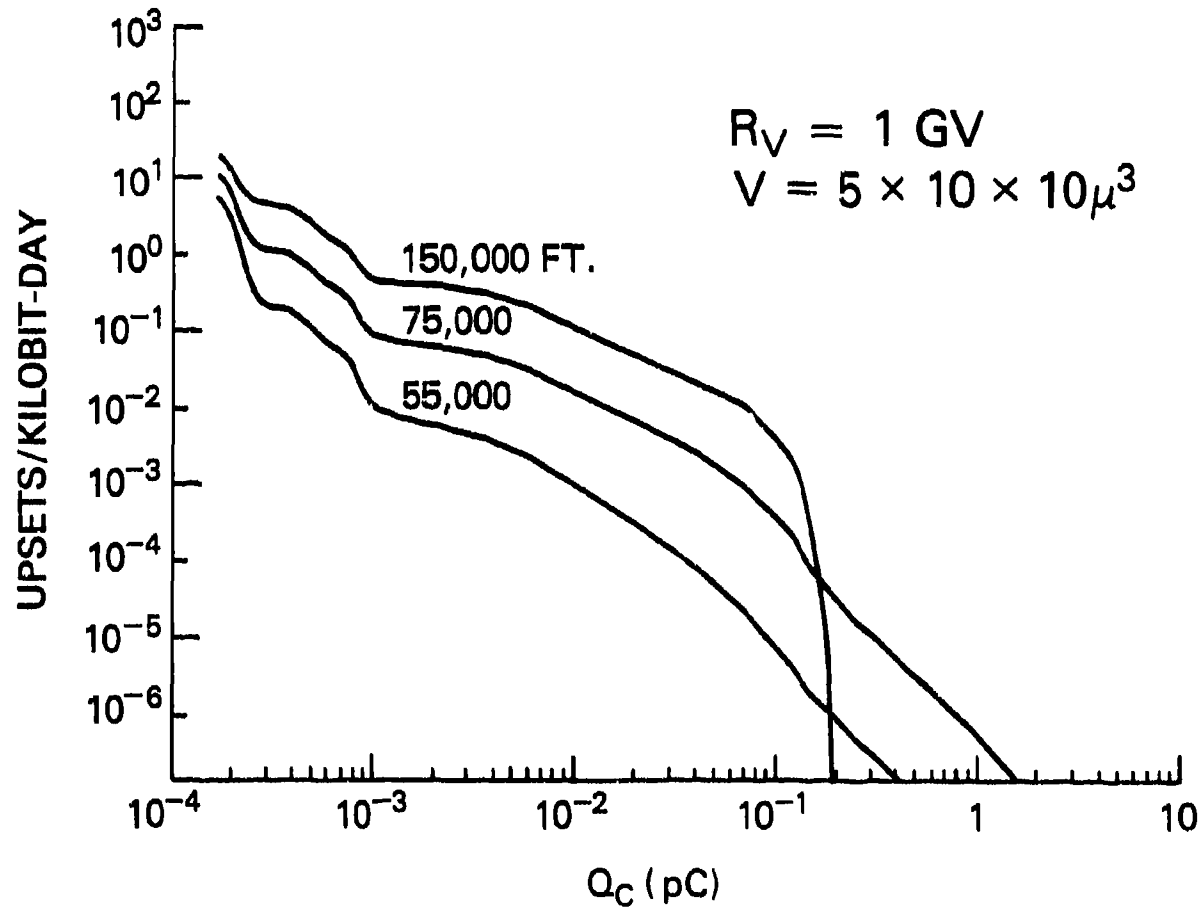

Figure 4.11 Variation of soft upset rate with altitude.

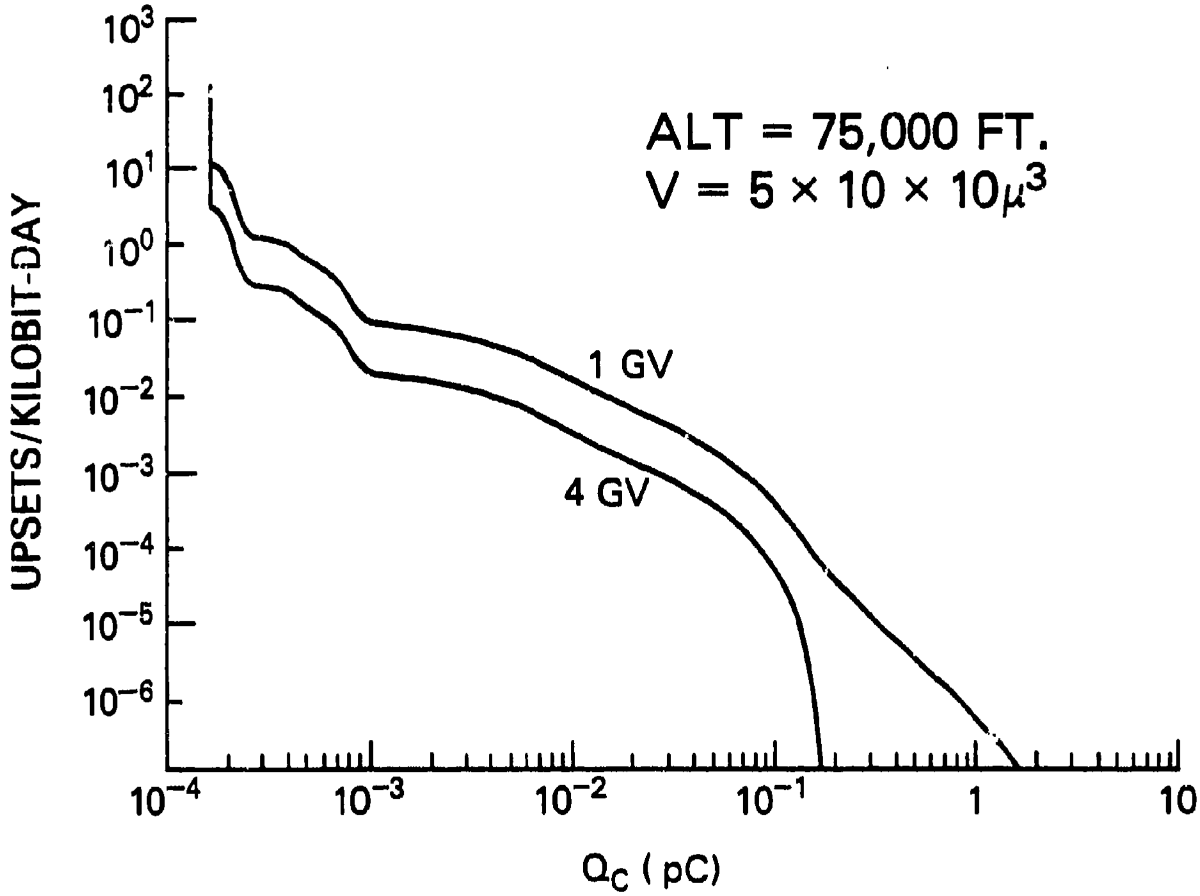

Figure 4.12 Variation of soft upset rate with geomagnetic cutoff.

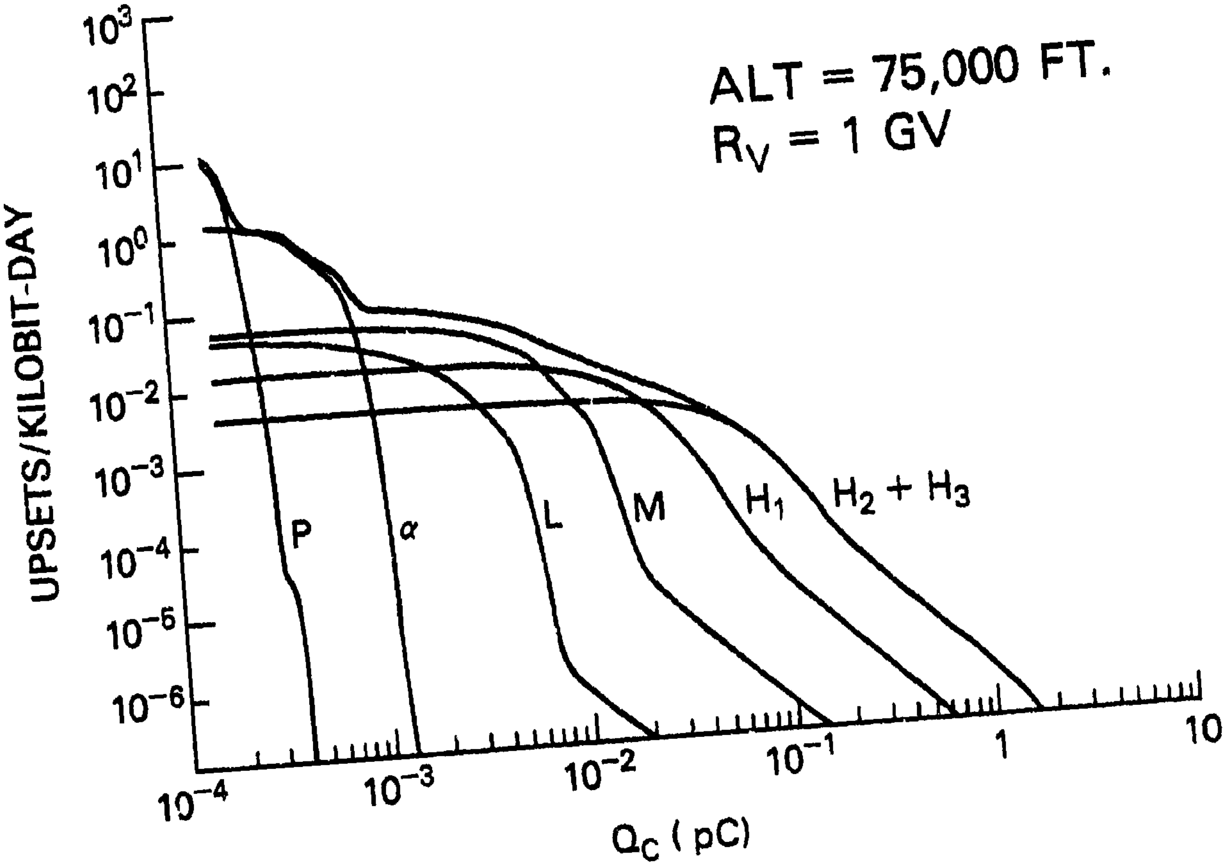

Figure 4.13 Variation of soft upset rate with element group.

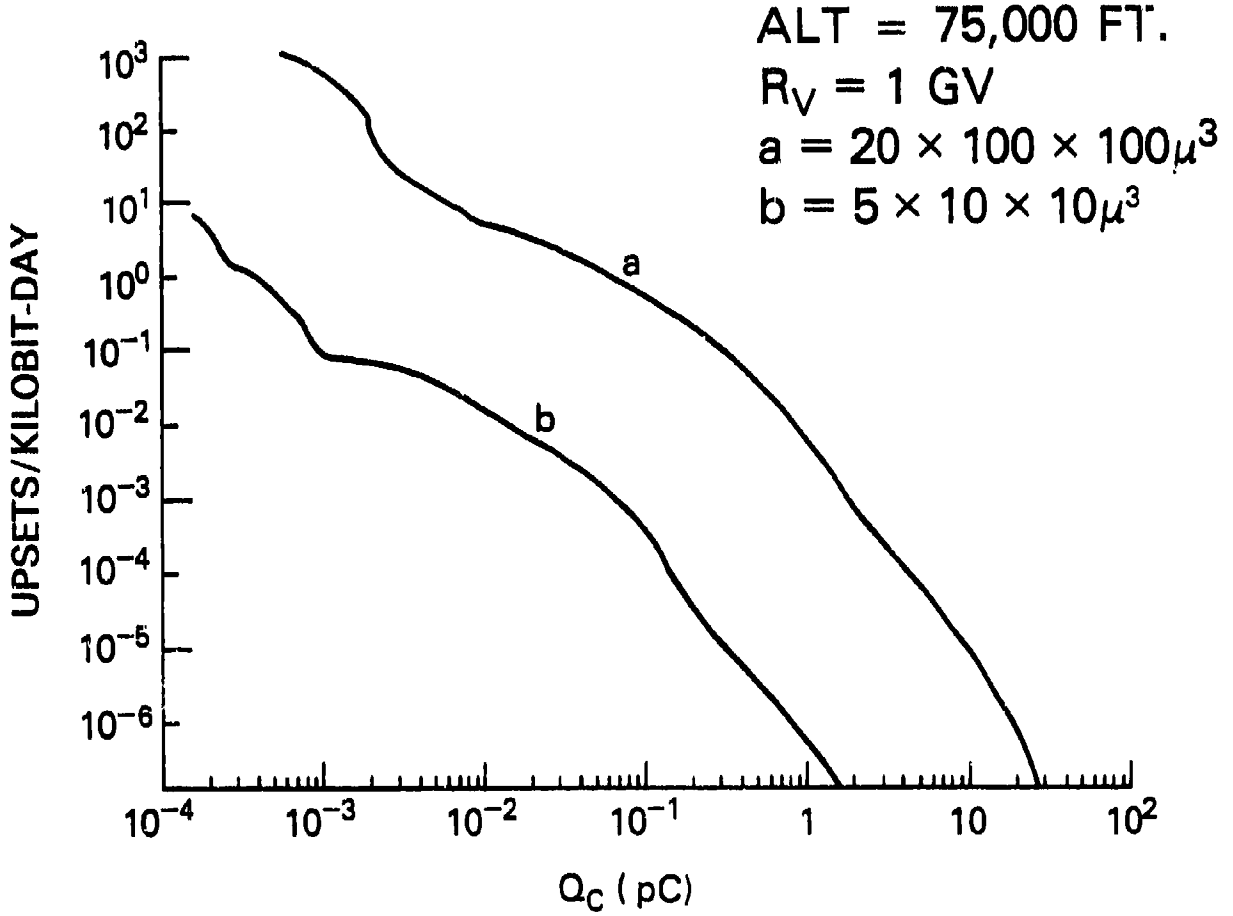

Figure 4.14 Variation of soft upset rate with sensitive volume.

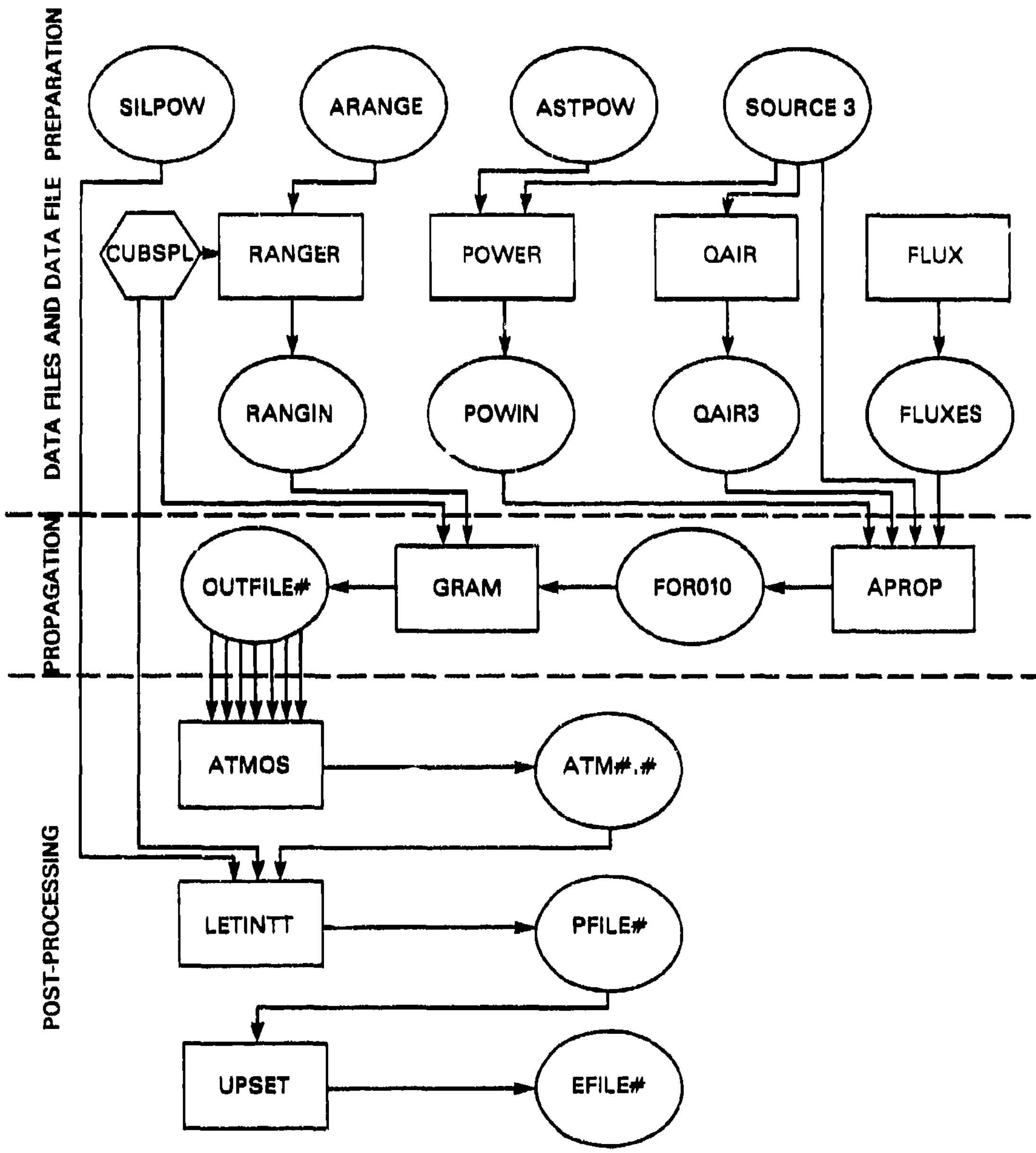

Figure 5.1 Flow chart of routines and data files used in making the calculation of this report.

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APPENDIX 1

```
      PROGRAM    GAIR
C     ****************************************************************
C     ***  THIS PROGRAM COMPUTES PARTIAL CROSS SECTIONS FOR CREATION
C     ***  OF ONE ISOTOPIC SPECIES FROM ANOTHER IN COLLISIONS WITH
C     ***  AIR NUCLEI.  IT IS BASED ON PROTON-NUCLEUS PARTIAL
C     ***  CROSS SECTIONS (YIELDX.FOR) COMPUTED FROM THE SEMI-
C     ***  EMPIRICAL FORMULAS.  THE LIST OF SPECIES (SOURCE3.DAT)
C     ***  IS REQUIRED INPUT.  GAIR3.DAT IS PRODUCED AS OUTPUT.
C     ****************************************************************
      PARAMETER  N=96,NI=96
      DIMENSION  IZ(5,N),IX(5,N),IY(5,N),FI(N),Q(N,N),S1(N),S2(N)
      DIMENSION  M1(N),M2(N),IQ(N,N),QF(N),FZ(26)
      DATA       FZ/7.E4,4.E3,18.7, 9.7,28.4,100.,25.2,92.1, 1.6, 1.4
     1,           2.8,19.8, 3.3,14.0, 0.8, 3.0, 1.7, 3.1, 2.2, 4.7
     1,           1.2, 3.3, 1.7, 3.3, 2.4,20.5/
      DATA       S1,S2/N*0.,N*0./
      OPEN(UNIT=1,FILE='SOURCE3.DAT',STATUS='OLD')
      OPEN(UNIT=2,FILE='GAIR3.DAT',STATUS='NEW')
C     ****************************************************************
C     ***  READ IN LIST OF SPECIES.
C     ****************************************************************
      READ (1,1) ((IZ(J,I),IX(J,I),IY(J,I),J=1,5),QF(I),I=1,N)
 1    FORMAT ((5(I3,A2,I3),F6.3))
C     ****************************************************************
C     ***  FOR EACH TARGET SPECIES I, COMPUTE THE CROSS SECTION TO
C     ***  CREATE THE PRODUCT SPECIES J AND UP TO 4 OTHER NUCLIDES
C     ***  WHICH ARE GROUPED WITH J IN THE SPECIES LIST.
C     ****************************************************************
      DO I=1,NI
        II=IZ(1,I)
        FI(I)=FZ(II)*QF(I)
        DO J=1,NI
          Q(J,I)=0.
          DO K=1,5
            IF (IY(K,J).EQ.0)  GO TO 12
            Z1=IZ(1,I)
            A1=IY(1,I)
            Z =IZ(K,J)
            A =IY(K,J)
            CALL YIELDX(IZ(1,I),IY(1,I),IZ(K,J),IY(K,J),2300.,QJ)
            ED=1.
            IF (IZ(K,J).GT.5 .AND. A.LT.A1/2.)  ED=3.*EXP(-2.*A/A1)
            EL=1.+.4*(1.+.02*(Z1/Z)**2)*(1.-1.5*Z/Z1)
            IF (IZ(K,J).LT.3 .OR.  IZ(K,J).GT.5 )    EL=1.
            Q(J,I)=Q(J,I)+QJ*2.*ED*EL
          END DO
 12       S1(I)=S1(I)+Q(J,I)
          S2(J)=S2(J)+Q(J,I)
        END DO
C     ****************************************************************
C     *** PUT IN INTEGER FORM.
C     ****************************************************************
        DO J=1,NI
          IQ(J,I)=Q(J,I)+.5
        END DO
C     ****************************************************************
C     ***  OUTPUT TO GAIR3.DAT
C     ****************************************************************
        WRITE(2,2) (IZ(K,I),IX(K,I),IY(K,I),K=1,5),FI(I),
     &  (IQ(J,I),J=1,NI)
 2      FORMAT (5(I3,A2,I3),30X,F10.2/4(20I4/),16I4)
        END DO
        END
```

APPENDIX 2

```
      PROGRAM FLUX
C     ************************************************************
C     ***  THIS PROGRAM CREATES AN INPUT FILE - FLUXES.DAT - FOR USE
C     ***  IN THE AIR PROPAGATION PROGRAM.  THE FUNCTION CRFE
C     ***  CONTAINS THE COSMIC RAY FLUX MODEL FROM NRL MEMORANDUM
C     ***  REPORT 4506 (COSMIC RAY EFFECTS ON MICROELECTRONICS,
C     ***  PART I).  THIS PROGRAM ALSO CREATES A FILE - OUTFILEO.DAT
C     ***  - WHICH CONTAINS THE INPUT FLUX IN THE STANDARD OUTPUT
C     ***  FILE FORMAT.
C     ***  *****  MODIFICATION  *****
C     ***  CRFE UPDATED TO GIVE MORE ACCURATE FLUX VALUES.
C     ************************************************************
      DIMENSION ENERGY(28),FLX(28),EPRIME(44)
      DIMENSION AMASS(28),RIGID(200),TRANS(200)
      INTEGER WEATHER
      DATA ENERGY/30.,40.,50.,60.,70.,80.,100.,120.,150.,
     & 200.,250.,300.,400.,500.,600.,700.,800.,1000.,1200.,
     & 1500.,2000.,2500.,3000.,4000.,5000.,6000.,7000.,8000./
      DATA EPRIME/1.,1.2,1.5,2.,2.5,3.,4.,5.,6.,7.,8.,10.,12.,
     & 15.,20.,25.,30.,40.,50.,60.,70.,80.,100.,120.,150.,200.,
     & 250.,300.,400.,500.,600.,700.,800.,1000.,1200.,1500.,
     & 2000.,2500.,3000.,4000.,5000.,6000.,7000.,8000./
      DATA AMASS/1.0079,4.0026,6.94,9.0122,10.81,12.011,
     & 14.0067,15.9994,18.9984,20.17,22.9898,24.305,26.9815,
     & 28.0855,30.9738,32.06,35.453,39.948,39.0983,40.08,
     & 44.9559,47.9,50.9415,51.996,54.938,55.847,58.9332,
     & 58.71/
      OPEN(UNIT=1,FILE='FLUXES.DAT',STATUS='NEW')
      OPEN(UNIT=2,FILE='OUTFILEO.DAT',STATUS='NEW')
C     ************************************************************
C     ***  ACCEPT INPUT DATA FROM COMMAND FILE:
C     ***     YEAR AND WEATHER ARE DISCUSSED IN CRFE.
C     ***     ORBIT=0 FOR AIR PROPAGATION, =1 IF GEOMAGNETIC
C     ***        TRANSMITTANCE FUNCTION IS TO BE FOLDED IN.
C     ************************************************************
      ACCEPT *,YEAR,WEATHER,ORBIT
      IF (ORBIT.EQ.1) THEN
        OPEN(UNIT=3,FILE='GTRANS.DAT',STATUS='OLD',READONLY)
        DO J=1,200
          READ(3,20) RIGID(J),TRANS(J)
        END DO
 20     FORMAT(4X,F6.3,5X,F8.6)
      ENDIF
C     ************************************************************
C     ***  COMPUTE FLUX AT HIGHEST 28 OF 44 ENERGIES.  FOLD IN
C     ***  GEOMAGNETIC TRANSMITTANCE IF NECESSARY.  OUTPUT AS
C     ***  FLUXES.DAT (HIGHEST ENERGY FIRST).
C     ************************************************************
      DO JG=1,28
        J=29-JG
        E=ENERGY(J)
        DO K=1,28
          Z=FLOAT(K)
          FLX(K)=CRFE(Z,E,YEAR,WEATHER)
          IF (ORBIT.EQ.1) THEN
            L=1
            RR=AMASS(K)*SQRT(E*(E+1863.))/Z/1000.
            DO WHILE (RIGID(L).LT.RR)
              L=L+1
            END DO
            FLX(K)=TRANS(L)*FLX(K)
```

```
          ENDIF
        END DO
        FLX(26)=FLX(26)+FLX(27)+FLX(28)
        WRITE(1,1) (FLX(I),I=1,26)
 1      FORMAT(4(7(1PE10.2)/))
      END DO
C     ***************************************************************
C     ***  COMPUTE FLUX AT ALL 44 ENERGIES.  FOLD IN GEOMAGNETIC
C     ***  TRANSMITTANCE IF NECESSARY.  OUTPUT AS OUTFILEO.DAT
C     ***  (LOWEST ENERGY FIRST).
C     ***************************************************************
      DO J=1,44
        E=EPRIME(J)
        DO K=1,28
          Z=FLOAT(K)
          FLX(K)=CRFE(Z,E,YEAR,WEATHER)
          IF (ORBIT.EQ.1) THEN
            L=1
            RR=AMASS(K)*SQRT(E*(E+1863.))/Z/1000.
            DO WHILE (RIGID(L).LT.RR)
              L=L+1
            END DO
            FLX(K)=TRANS(L)*FLX(K)
          ENDIF
        END DO
        FLX(26)=FLX(26)+FLX(27)+FLX(28)
        WRITE(2,1) (FLX(I),I=1,26)
      END DO
      END


      FUNCTION CRFE(Z,EZ,Y,M)
C     ***************************************************************
C     ***  THIS ROUTINE RETURNS THE DIFFERENTIAL FLUX IN PARTICLES/
C     ***  M**2.STER.SEC.MEV/U IN THE INTERPLANETARY MEDIUM
C     ***  NEAR EARTH
C     ***  FOR IONS OF ATOMIC NUMBER=Z
C     ***  FOR ENERGY (IN MEV/U)=EZ
C     ***  FOR YEAR=Y
C     ***  AND FOR WEATHER CONDITION=M
C     ***
C     ***  THE INTERPLANETARY WEATHER CONDITIONS CONSIDERED ARE:
C     ***  M=1; GALACTIC COSMIC RAYS (GCR) ONLY
C     ***  M=2; GCR + FULLY-IONIZED ANOMALOUS COMPONENT
C     ***  M=3; GCR + 90% WORST CASE SOLAR ACTIVITY
C     ***  M=4; GCR + SINGLY-IONIZED ANOMALOUS COMPONENT
C     ***  M=5; PEAK ORDINARY FLARE FLUX AND MEAN COMPOSITION
C     ***  M=6; PEAK ORDINARY FLARE FLUX AND WORST-CASE COMPOSITION
C     ***  M=7; PEAK WORST-CASE FLARE FLUX AND MEAN COMPOSITION
C     ***  M=8; PEAK WORST-CASE FLARE FLUX AND WORST-CASE COMPOSITION
C     ***  M=9; PEAK ANOMALOUS FLARE FLUX AND MEAN COMPOSITION
C     ***  M=10; PEAK ANOMALOUS FLARE FLUX AND WORST-CASE COMPOSITION
C     ***  M=11; MEAN ORDINARY FLARE FLUX AND MEAN COMPOSITION
C     ***  M=12; MEAN ORDINARY FLARE FLUX AND WORST-CASE COMPOSITION
C     ***  M=13; MEAN WORST-CASE FLARE FLUX AND MEAN COMPOSITION
C     ***  M=14; MEAN WORST-CASE FLARE FLUX AND WORST-CASE COMPOSITION
C     ***  M=15; MEAN ANOMALOUS FLARE FLUX AND MEAN COMPOSITION
C     ***  M=16; MEAN ANOMALOUS FLARE FLUX AND WORST-CASE COMPOSITION
C     ***  Z IS THE PARTICLE ATOMIC NUMBER
C     ***  EZ IS THE ENERGY IN MEV/U
```

```
C        ***   Y IS THE YEAR OF THE SPECTRA;
C        ***     1975.144 = SOLAR MIN ,  1980.598 = SOLAR MAX
C        ***
C        ***   THIS ROUTINE IS BASED ON THE MODEL IN
C        ***   "COSMIC RAY EFFECTS ON MICROELECTRONICS" BY
C        ***   J. H. ADAMS, JR., R. SILBERBERG, AND C. H. TSAO
C        ***   NRL REPORT NO. 4506, AUGUST 25, 1981, EQUATION NOS.
C        ***   AND TABLE NOS  REFERRED TO BELOW ARE IN THE APPENDIX.
C        ***************************************************************
         DIMENSION AO(3),EO(3),B(3),X1(6),X2(3),C1(3),C2(3),R(92),
      &  INDX(92),FR(92,2),EPX(40),FPX(40)
C        ***************************************************************
C        ***   XTSAO IS THE C.H. TSAO CORRECTION FACTOR (12/81)
C        ***************************************************************
         DIMENSION XTSAO(28)
         DATA XTSAO/.69,15*.79,3*.38,.47,5*.38,3*.47/
         DATA IST/0/,IPTS/0/
C        ***************************************************************
C        ***   THESE ARE THE COEFFICIENTS  IN TABLE 1 OF THE REPORT
C        ***************************************************************
         DATA (AO(I),I=1,3)/-2.2,-2.25,-2.70/
         DATA (EO(I),I=1,3)/1.175E5,7.94E4,1.1E5/
         DATA (B(I),I=1,3)/2.75,2.3,2.3/
         DATA (X1(I),I=1,6)/.117,.079,.22,.155,.140,.117/
         DATA (X2(I),I=1,3)/.80,.83,.65/
         DATA (C1(I),I=1,3)/6.52,5.0,7.0/
         DATA (C2(I),I=1,3)/4.,5.,8./
C        ***************************************************************
C        ***   ELEMENTAL RATIOS FROM TABLES 2,3,4,AND5
C        ***************************************************************
         DATA (R(I),I=1,28)/1.,1.,.33,.17,.5,.025,1.,.023,4.1E-4,
      &  3.5E-3,7.0E-4,4.7E-3,8.3E-4,3.5E-3,2.E-4,7.4E-4,.07,.13,
      &  .09,.23,.08,.14,.07,.14,.1,1.,6.E-3,4.8E-2/
C        ***************************************************************
C        ***   THE ELEMENTAL RATIOS HAVE BEEN EXTENDED TO URANIUM USING
C        ***   THE HEAO-3 DATA INTERPRETED WITH CAMERON'S ABUNDANCES
C        ***************************************************************
         DATA (R(I),I=29,92)/2.E-4,5.E-4,4.E-5,1.2E-4,6.E-6,5.E-5,
      * 8.E-6,3.E-5,5.E-6,4.E-5,2.E-6,2.E-5,1.E-6,1.5E-5,0.,2.E-6,
      * 4.4E-7,8.E-6,1.E-7,3.E-6,2.1E-7,6.E-6,3.4E-7,5.E-6,4.E-6,7.E-6,
      * 4.E-7,6.5E-6,4.E-7,2.2E-6,2.E-7,2.E-6,0.,1.8E-6,2.E-7,
      * 1.8E-6,2.E-7,2.E-6,2.E-7,1.2E-6,2.E-7,1.3E-6,1.E-7,9.E-7,
      * 9.E-8,9.E-7,9.E-8,1.E-6,8.E-7,1.6E-6,2.E-7,1.4E-6,2.E-7,
      * 8.E-7,1.5E-7,0.,0.,0.,0.,0.,0.,5.E-8,0.,3.E-8/
C        ***************************************************************
C        ***   INDX ASSOCIATES EACH ELEMENT IN COSMIC RAYS WITH A SET OF
C        ***   COEFFICIENTS
C        ***************************************************************
         DATA (INDX(I),I=1,92)/1,15*2,76*3/
C        ***************************************************************
C        ***   ORDINARY AND WORST-CASE SOLAR FLARE ABUNDANCES, TABLE 6
C        ***************************************************************
         DATA((FR(I,J),I=1,28),J=1,2)/1.0,.022,0.0,0.0,0.0,
      * 1.6E-4,3.8E-5,3.2E-4,0.0,5.1E-5,1.6E-6,4.8E-5,3.5E-6,
      * 3.8E-5,2.3E-7,1.8E-5,1.7E-7,3.9E-6,1.3E-7,2.3E-6,0.0,1.E-7,
      * 0.0,5.7E-7,4.2E-7,4.1E-5,1.E-7,2.2E-6,1.0,3.3E-2,0.0,0.0,0.0,
      * 4.E-4,1.1E-4,1.0E-3,0.0,1.9E-4,6.1E-6,1.8E-4,1.4E-5,1.6E-4,
      * 1.1E-6,8.4E-5,8.E-7,1.8E-5,6.E-7,1.E-5,0.0,5.E-7,0.0,3.2E-6,
      * 2.3E-6,2.3E-4,5.5E-7,1.2E-5/
C        ***************************************************************
C        ***   THE ORDINARY FLARE ABUNDANCESARE EXTENDED TO URANIUM
```

APPENDIX 2 (Cont'd)

```
C        ***  USING CAMERON'S TABLE OF GENERAL ABUNDANCES.
C        ***********************************************************
         DATA (FR(I,1),I=29,92)/2.E-8,6.E-8,2.E-9,5.E-9,3.E-10,3.E-9,
     * 4.E-10,2.E-9,3.E-10,1.E-9,2.E-10,5.E-10,4.E-11,2.E-10,
     * 0.,9.E-11,2.E-11,6.E-11,2.E-11,7.E-11,9.E-12,2.E-10,1.4E-11,
     * 3.E-10,6.E-11,2.7E-10,2.E-11,2.E-10,2.E-11,5.E-11,8.E-12,
     * 4.E-11,0.,1.E-11,4.E-12,2.E-11,3.E-12,2.E-11,4 E-12,1.E-11,
     * 2.E-12,9.E-12,2.E-12,8.E-12,9.E-13,1.E-11,2.E-12,3.E-11,
     * 3.E-11,6.E-11,1.E-11,1.E-11,9.E-12,1.E-10,6.E-12,0.,0.,0.,
     * 0.,0.,0.,2.E-12,0.,1.2E-12/
C        ***********************************************************
C        ***  WORST CASE ABUNDANCES WILL BE EXTENDED TO URANIUM BY
C        ***  SCALING THE ORDINARY ABUNDANCES ACCORDING TO AN
C        ***  ENHANCEMENT FACTOR OF 0.22Z.
C        ***********************************************************
         DO 300 I=29,92
         FR(I,2)=FR(I,1)*0.22*I
300      CONTINUE
         E=EZ
C        ***********************************************************
C        ***  THE PARTICLE MODEL ONLY GOES DOWN TO 10 MEV
C        ***********************************************************
         IF(EZ.LT.10.) E=10.
         IZ=Z+.5
C        ***********************************************************
C        ***  SELECT THE MODEL ELEMENTAL SPECTRUM
C        ***********************************************************
         I INDX(IZ)
         IJ=I+2
         II=IJ-1
C        ***********************************************************
C        ***  EQS. 4, 5, AND 6 OF THE REPORT
C        ***********************************************************
         XM=C1(I)*EXP(-X2(I)*(ALOG10(E))**2)-C2(I)
1        FORMAT(2X,E12.5,2X,E12.5)
         AM=A0(I)*(1-EXP(-X1(II)*(ALOG10(E))**B(I)))
         AX=A0(I)*(1-EXP(-X1(IJ)*(ALOG10(E))**B(I)))
         FMIN=10**XM
         FMAX=FMIN*(E/E0(I))**AX
         FMIN=FMIN*(E/E0(I))**AM
C        ***********************************************************
C        ***  ADD FULLY-IONIZED ANOMALOUS HELIUM HERE
C        ***********************************************************
         IF((M.NE.2).OR.(IZ.NE.2))GOTO 10
         IF(E.LT.200.)FMIN=.4
         IF(E.LT.300.)FMAX=.08
10       CONTINUE
C        ***********************************************************
C        ***  DO THE 90% WORST-CASE (I.E. SOLAR MINIMUM AND LOW ENERGY
C        ***  STUFF, EQS. 11 AND 12)
C        ***********************************************************
         IF(M.NE.3)GOTO 16
         IF(E.GT.100.)GOTO 15
         IF(I.GT.1)GOTO 11
         F=FMIN*(1897*EXP(-E/9.66)+1.64)
         GOTO 20
11       F=FMIN*(28.4*EXP(-E/13.84)+1.64)
         GOTO 20
15       F=FMIN*1.64
         GOTO 20
C        ***********************************************************
```

APPENDIX 2 (Cont'd)

```
C       ***  PURE GALACTIC COSMIC RAYS IN YEAR Y, EQS  1, 2, AND 3
C       ************************************************************
16      AX=.5*(FMIN-FMAX)
        BX=.5*(FMIN+FMAX)
        W=.576*(Y-1950.6)
        F=AX*SIN(W)+BX
C       ************************************************************
C       ***  DO LI, BE, AND B, EQ. 7 AND TABLE 4
C       ************************************************************
20      IF((IZ.LT.3).OR.(IZ.GT.5))GOTO 30
        IF(E.GT.6000.)GOTO 25
        F=.0142*F
        GOTO 30
25      F=F*(.67*E**(-.443))
C       ************************************************************
C       ***  DO NITROGEN, EQ. 8
C       ************************************************************
30      IF(IZ.NE.7)GOTO 40
        F=F*(.0064*EXP(-.4*(ALOG10(E)-3.15)**2)+.0056*
     &  EXP(-.9*(ALOG10(E)-.8)**2))
C       ************************************************************
C       ***  ADD THE ANOMALOUS FEATURE TO NITROGEN, EQ. 15
C       ************************************************************
        IF(M.NE.2) GO TO 45
        FT=(1.54E-2)*EXP(-(ALOG(E)-1.79)**2/.7)
        IF(FT.GT.F) F=FT
        GO TO 45
C       ************************************************************
C       ***  ADD THE ANOMALOUS FEATURE TO NITROGEN, EQ. 14
C       ************************************************************
 40     IF((M.NE.2).OR.(IZ.NE.8)) GO TO 45
        FT=(6.0E-2)*EXP(-(ALOG(E)-1.79)**2/.7)/.023
        IF(FT.GT.F) F=FT
C       ************************************************************
C       ***  DO THE SUB-IRON NUCLEI, EQS. 9 AND 10
C       ************************************************************
45      IF(IZ.EQ.20)GOTO 50
        IF((IZ.LT.17).OR.(IZ.GT.25))GO TO 50
        F=F*(16.*(1.-EXP(-.126*E**.4))*E**(-.33))
50      CRFE=R(IZ)*F*XTBAD(IZ)
C       ************************************************************
C       ***  IF M.GT.4 ADD THE CONTRIBUTION FROM FLARES
C       ************************************************************
        IF(M.GT.4) GO TO 100
C       ************************************************************
C       ***  THIS COMPLETES THE COSMIC RAY SECTION, RETURN
C       ************************************************************
        RETURN
C       ************************************************************
C       ***  THIS SECTION RETURNS SOLAR FLARE ENVIRONMENTS
C       ***
C       ***  CONSTRUCT FLARE CASE INDEX, MK, AND HEAVY ION ENRICHMENT
C       ***  INDEX, IK
C       ************************************************************
 100    MK=(M+1)/2-2
        IK=M-2*(MK+1)
        CRFE=0.0+CRFE
C       ************************************************************
C       ***  BRANCH TO THE FLARE CASE
C       ************************************************************
        GO TO (110,120,130,140,150,160),MK
```

```
C        ************************************************************
C        ***  ORDINARY FLARES
C        ************************************************************
 110     IF(E.GT.1000.) GO TO 200
         F=(1.94E+4)*(EXP(-E/27.5)+173.*EXP(-E/4.))
         CRFE=FR(IZ,IK)*F+CRFE
         RETURN
C        ************************************************************
C        ***  90 PERCENT WORST-CASE FLARES-PEAK FLUX, EQ. 22
C        ************************************************************
 120     IF(E.GT.1000 ) GO TO 200
         F=(1.71E+5)*(EXP(-E/24.5)+63.6*EXP(-E/4))
         CRFE=FR(IZ,IK)*F+CRFE
         RETURN
C        ************************************************************
C        ***  ANOMALOUSLY LARGE FLARES-PEAK FLUX EQ. 24
C        ************************************************************
 130     PR=SQRT((.001*E)**2+(1.86E-3)*E)
         EX=E+.01
         PRX=SQRT((.001*EX)**2+(1.86E-3)*EX)
         DPDE=(PRX-PR)*100
         IF(E.GT.150.) GO TO 131
         F=(9.3E+9)*DPDE*EXP(-PR*10.)
         GO TO 132
 131     F=(1.76E+5)*DPDE*PR**(-9.)
 132     CRFE=FR(IZ,IK)*F+CRFE
         RETURN
C        ************************************************************
C        ***  ORDINARY FLARES-MEAN FLUX, EQ. 19
C        ************************************************************
 140     IF(E.GT.600.) GO TO 200
         F=(3.3E+9)*(EXP(-E/20.2)+307.*EXP(-E/3.))
         F=F/3.2E+5
         CRFE=FR(IZ,IK)*F+CRFE
         RETURN
C        ************************************************************
C        ***  90 PERCENT WORST-CASE FLARES-MEAN FLUX, EQ. 20
C        ************************************************************
 150     IF(E.GT.1000 ) GO TO 200
         F=(7.6E+9)*(EXP(-E/30.)+165*EXP(-E/4.))
         F=F/3.2E+5
         CRFE=FR(IZ,IK)*F+CRFE
 200     RETURN
C        ************************************************************
C        ***  ANOMALOUSLY LARGE FLARES-MEAN FLUX, EQ. 23
C        ************************************************************
 160     IF(E.GT.1000.) GO TO 200
         F=(2.37E+11)*EXP((30.-E)/26.5)
         F=F/3.2E+5
         CRFE=FR(IZ,IK)*F+CRFE
         RETURN
C        ************************************************************
C        ***  THIS ENTRY RETURNS THE ORBIT-AVERAGED TRAPPED PROTON FLUX
C        ***  AT THE SKIN OF THE SPACECRAFT. THE FLUX IS INTERPOLATED
C        ***  FROM THE TABULATION IN THE STASS.DAT FILE.
C        ************************************************************
         ENTRY PROTON(EZ)
         IF(IST.EQ.1) GO TO 204
         IST=1
         OPEN (UNIT=10,READONLY,SHARED,STATUS='OLD',FILE='STASS.DAT')
         I=1
```

```
201     READ(10,202,END=203) EPX(I),FPX(I)
202     FORMAT(1X,F6.1,1X,E10.3)
        FPX(I)=795775.*FPX(I)
        I=I+1
        GO TO 201
203     IPTS=I-1
204     DO 205 I=2,IPTS
        IF(EZ.GE.EPX(I)) GO TO 205
        ISAV=I
        GO TO 206
205     CONTINUE
        PROTON=0.0
        RETURN
206     PROTON=(FPX(ISAV)-FPX(ISAV-1))*(EZ-EPX(ISAV-1))/(EPX(ISAV)
     *-EPX(ISAV-1))+FPX(ISAV-1)
        RETURN
        END
```

APPENDIX 3

```
      PROGRAM   RANGER
C     ***************************************************************
C     ***  THIS PROGRAM CONVERTS A RANGE.DAT FILE INTO THE
C     ***  RANGIN.DAT FILE NEEDED IN MATTER PROPAGATION.
C     ***  THE RANGE.DAT FILE IS OBTAINED USING TRANSFER.FOR
C     ***  ON RANGE-ENERGY TABLES GENERATED BY J. ADAMS.
C     ***  THE STPOW.DAT FILE IS ALSO NEEDED - IT IS GOTTEN
C     ***  FROM STOPPING POWER TABLES USING TRANSFER.FOR
C     ***************************************************************
      DIMENSION C(6,44),S(4,44),SS(44),EP(26,44),E(44)
      DIMENSION ZA(26),ZB(26),IA(26),IB(26)
      DIMENSION EQ(26,44)
      DATA ZA/1.,4*2.,2*6.,10*8.,8*18.,26./
      DATA ZB/1.,2.,4*6.,2*8.,10*18.,8*26./
      DATA IA/1,4*2,2*3,10*4,8*5,6/
      DATA IB/1,2,4*3,2*4,10*5,8*6/
      OPEN(UNIT=3,FILE='RANGE.DAT',READONLY,STATUS='OLD')
      OPEN(UNIT=2,FILE='STPOW.DAT',READONLY,STATUS='OLD')
      OPEN(UNIT=7,FILE='RANGIN.DAT',STATUS='NEW')
C     ***************************************************************
C     ***  READ IN RANGE DATA AND ZERO OUTPUT MATRIX
C     ***************************************************************
      DO 10 J=1,44
        READ(3,1) E(J),(C(I,J),I=1,6)
 1      FORMAT(F8.3,6(3X,1PE9.3))
        DO I=1,26
          EP(I,J)=0.
        END DO
      END DO
C     ***************************************************************
C     ***  FIND ENERGY CORRESPONDING CURRENT PARTICLE ENERGY PRIOR
C     ***  TO PASSING THROUGH 1 GM MATERIAL.
C     ***************************************************************
      DO J=1,26
        ZH=ZB(J)
        ZL=ZA(J)
        Z=FLOAT(J)
        IL=IA(J)
        IH=IB(J)
        DO K=1,44
          IF(IH.EQ.IL) S(1,K)=C(IL,K)
          IF(IH.NE.IL) S(1,K)=((ZH-Z)*C(IL,K)+(Z-ZL)*C(IH,K))/(ZH-ZL)
          SS(K)=S(1,K)
        END DO
        CALL CUBSPL(E,S,44)
        DO K=1,44
          R=SS(K)+1.
          DO 40 IK=K,44
            IF(SS(IK).GE.R) GO TO 50
          END DO
 50       IK=IK-1
          EH=E(IK+1)
          EL=E(IK)
          DO KK=1,10
            EE=.5*(EL+EH)
            RP=((S(4,IK)*EE+S(3,IK))*EE+S(2,IK))*EE+S(1,IK)
            IF(RP.LE.R) EL=EE
            IF(RP.GT.R) EH=EE
          END DO
          EP(J,K)=.5*(EL+EH)
        END DO
```

```
          END DO
C         ************************************************************
C         ***  READ IN STOPPING POWER DATA
C         ************************************************************
          DO J=1,44
            READ(2,1) E(J),(C(I,J),I=1,6)
          END DO
C         ************************************************************
C         ***  FIND RATIO OF STOPPING POWER PRIOR TO 1 GM MATERIAL, TO
C         ***  CURRENT STOPPING POWER.  THIS FACTOR ACCOUNTS FOR ENERGY
C         ***  INTERVAL SPREAD IN COMPUTING DIFFERENTIAL FLUX.
C         ************************************************************
          DO J=1,26
            ZH=ZB(J)**2
            ZL=ZA(J)**2
            Z=FLOAT(J)**2
            IL=IA(J)
            IH=IB(J)
            DO K=1,44
              IF(IH.EQ.IL) S(1,K)=C(IL,K)
              IF(IH.NE.IL) S(1,K)=((ZH-Z)*C(IL,K)+(Z-ZL)*C(IH,K))/(ZH-ZL)
              SS(K)=S(1,K)
            END DO
            CALL CUBSPL(E,S,44)
            DO K=1,44
              R=EP(J,K)
              DO IKK=1,44
                IK=45-IKK
                IF(E(IK).LE.R) GO TO 150
              END DO
 150          RR=((S(4,IK)*R+S(3,IK))*R+S(2,IK))*R+S(1,IK)
              EQ(J,K)=RR/SS(K)
            END DO
          END DO
C         ************************************************************
C         ***  OUTPUT ENERGY PRIOR TO .1 GM OF AIR
C         ************************************************************
          DO K=1,44
            KK=45-K
            WRITE(7,2) E(K),(EP(J,K),J=1,26)
          END DO
C         ************************************************************
C         ***  OUTPUT RATIO OF STOPPING POWERS
C         ************************************************************
          DO K=1,44
            WRITE(7,2) E(K),(EQ(J,K),J=1,26)
 2          FORMAT(4(7(1PE10.2)/))
          END DO
          END
```

APPENDIX 4

```
      PROGRAM    POWER
C     ************************************************************
C     ***  THIS PROGRAM CONVERTS A STPOW.DAT FILE INTO THE
C     ***  POWIN.DAT FILE NEEDED IN MATTER PROPAGATION.  THE
C     ***  FILE SOURCE3.DAT (AN ISOTOPE LIST) IS ALSO REQUIRED.
C     ***  THE STPOW.DAT FILE IS OBTAINED USING THE TRANSFER.FOR
C     ***  PROGRAM ON STOPPING POWER TABLES CREATED BY J. ADAMS.
C     ************************************************************
      DIMENSION  W(28,104),E(28),DE(28),C(6,28)
      DIMENSION  IZ(104),IA(104),Z1(26),Z2(26),I1(26),I2(26)
      DATA      Z1/1.,4*2.,2*6.,10*8.,8*18.,26./
      DATA      Z2/1.,2.,4*6.,2*8.,10*18.,8*26./
      DATA      I1/1,4*2,2*3,10*4,8*5,6/
      DATA      I2/1,2,4*3,2*4,10*5,8*6/
      OPEN(UNIT=1,FILE='SOURCE3.DAT',READONLY,STATUS='OLD')
      OPEN(UNIT=2,FILE='STPOW.DAT',READONLY,STATUS='OLD')
      OPEN(UNIT=4,FILE='POWIN.DAT',STATUS='NEW')
C     ************************************************************
C     ***  READ IN ISOTOPE LIST
C     ************************************************************
      DO J=1,104
        READ (1,1) IZ(J),IA(J)
 1      FORMAT (I3,2X,I3)
      END DO
C     ************************************************************
C     *** READ IN STOPPING POWER DATA IGNORING 16 LOWEST ENERGIES
C     ************************************************************
      DO J=1,16
        READ (2,2) Q1,Q2,Q3,Q4,Q5,Q6,Q7
      END DO
      DO J=1,28
        READ (2,2) E(J),(C(I,J),I=1,6)
 2      FORMAT (F8.1,1P6E12.3)
      END DO
C     ************************************************************
C     ***  DETERMINE INTERVALS BETWEEN ENERGIES
C     ************************************************************
      DO JJ=1,27
        J=28-JJ
        DE(J)=E(J+1)-E(J)
      END DO
      DE(28)=1000.
C     ************************************************************
C     ***  INTERPOLATE STOPPING POWER TABLES TO ALL ISOTOPES
C     ************************************************************
      DO J=1,104
        I=IZ(J)
        ZH=Z2(I)**2
        ZL=Z1(I)**2
        Z=FLOAT(I)**2
        IH=I2(I)
        IL=I1(I)
        DO 100 K=1,28
        IF (IH.EQ.IL) W(K,J)=C(IL,K)
        IF (IH.NE.IL) W(K,J)=((ZH-Z)*C(IL,K)+(Z-ZL)*C(IH,K))/(ZH-ZL)
        W(K,J)=W(K,J)/IA(J)
      END DO
C     ************************************************************
C     ***  OUTPUT STOPPING POWER TABLES TO POWIN.DAT
C     ************************************************************
      DO JJ=1,28
        J=29-JJ
        WRITE(4,4) E(J),DE(J),(W(J,K),K=1,104)
 4      FORMAT (F8.1,5X,F8.1,13(/8(1PE9.2)))
      END DO
      END
```

APPENDIX 5

```
      PROGRAM APROP
C     ************************************************************
C     ***  THIS PROGRAM PROPAGATES A PARTICLE FLUX TAKEN FROM
C     ***  FLUXES.DAT THROUGH A PATHLENGTH OF GRAMS gm/cm**2.
C     ***  IONIZATION LOSS IN THE LAST GRAM IS POSTPONED FOR
C     ***  THE PROGRAM GRAM.FOR.
C     ************************************************************
      DIMENSION F(250,104),FL1(240,104),FL2(104),FF(26)
      DIMENSION FS(104),P(104),SP(26),S(104)
      COMMON/ALK/PIN(104),POUT(104),IZ(104),IA(104)
      COMMON/BLK/Q(104,104)
      COMMON/CLK/SDEX,RDEX,RP,EMAX,DX
C     ************************************************************
C     ***  DATA STATEMENT DEFINES TREATMENT OF HIGH ENERGY PARTICLES
C     ***  AND PATHLENGTH STEP, DX.
C     ***  SDEX=SPECTRAL INDEX AT EMAX
C     ***  RDEX=RANGE ENERGY INDEX AT EMAX
C     ***  RP=PROTON RANGE IN AIR AT EMAX
C     ***  EMAX=HIGHEST ENERGY TREATED EXPLICITLY.  BEYOND THIS A
C     ***       POWER LAW SPECTRUM AND APPROXIMATE IONIZATION LOSS
C     ***       ARE USED.
C     ************************************************************
      DATA SDEX,RDEX,RP,EMAX,DX/2.5,1.,4.089E3,8000.,.1/
C     ************************************************************
C     ***  ACCEPT PATHLENGTH IN GRAMS.  NOTE DIMENSIONS OF F AND FL1
C     ***  MUST BE AT LEAST F(IGRAM,104),FL1(IGRAMM,104).
C     ************************************************************
      ACCEPT *,GRAMS
      IGRAM=INT(10.*GRAMS)
      IGRAMM=IGRAM-10
C     ************************************************************
C     ***  READ IN DATA ON ISOTOPES TO BE PROPAGATED FROM SOURCE3.DAT
C     ***  AND STOPPING POWER INFORMATION FROM POWIN.DAT.
C     ************************************************************
      OPEN(UNIT=1,FILE='SOURCE3.DAT',READONLY,STATUS='OLD')
      OPEN(UNIT=4,FILE='POWIN.DAT',READONLY,STATUS='OLD')
      DO J=1,104
        READ(1,1) IZ(J),IA(J),P(J)
 1      FORMAT(I3,2X,I3,32X,F6.3)
        DO K=1,IGRAMM
          FL1(K,J)=0.
        END DO
      END DO
C     ************************************************************
C     ***  SET UP CROSS SECTION MATRIX (FRAGMENTATION OF NUCLEI)
C     ************************************************************
      CALL AIRMAT
      OPEN(UNIT=2,FILE='FLUXES.DAT',READONLY,STATUS='OLD')
      DO I=1,28
C     ************************************************************
C     ***  READ IN ELEMENTAL ABUNDANCES FROM FLUXES.DAT AND CONVERT
C     ***  INTO ISOTOPIC ABUNDANCES USING APPROXIMATE ISOTOPIC
C     ***  FRACTIONS P(104) FROM SOURCE3.DAT.
C     ************************************************************
        READ(2,2) (SP(K),K=1,26)
 2      FORMAT(4(7(1PE10.2)/))
        DO K=1,104
          IZZ=IZ(K)
          S(K)=SP(IZZ)*P(K)
          FL2(K)=S(K)
          DO J=1,IGRAM
```

```
          F(J,K)=0.
        END DO
      END DO
C     ****************************************************************
C     ***  SET UP IONIZATION LOSS VECTORS
C     ****************************************************************
      CALL ILOSS
C     ****************************************************************
C     ***  FRAGMENTATION AND IONIZATION LOSS FOR ALL BUT LAST GRAM
C     ****************************************************************
      DO J=1,IGRAMM
        DO KA=1,104
          FS(KA)=PIN(KA)*FL1(J,KA)+POUT(KA)*FL2(KA)
        END DO
        DO KA=1,104
          DO KB=1,104
            F(J,KA)=F(J,KA)+G(KA,KB)*FS(KB)
          END DO
          FL2(KA)=F(J,KA)
        END DO
      END DO
C     ****************************************************************
C     ***  SET UP BOUNDARY CONDITIONS FOR NEXT LOWER ENERGY
C     ****************************************************************
      DO J=1,IGRAMM
        DO KA=1,104
          FL1(J,KA)=F(J,KA)
        END DO
      END DO
C     ****************************************************************
C     ***  PERFORM FRAGMENTATION ONLY FOR LAST GRAM
C     ****************************************************************
      DO J=IGRAMM+1,IGRAM
        DO KA=1,104
          DO KB=1,104
            F(J,KA)=F(J,KA)+G(KA,KB)*F(J-1,KB)
          END DO
        END DO
      END DO
C     ****************************************************************
C     ***  PUT SUM OVER ELEMENTS INTO FF(26)
C     ****************************************************************
      DO JZ=1,26
        FF(JZ)=0.
      END DO
      DO K=1,104
        IZZ=IZ(K)
        FF(IZZ)=FF(IZZ)+F(IGRAM,K)
      END DO
C     ****************************************************************
C     ***  OUTPUT RESULTS FOR CURRENT ENERGY
C     ****************************************************************
      WRITE(10,5) (FF(K),K=1,26)
    5 FORMAT(4(7(1PE10.2)/))
C     ****************************************************************
C     ***  PROCEED TO NEXT OF 28 ENERGIES
C     ****************************************************************
    END DO
    END
```

APPENDIX 6

```
      SUBROUTINE AIRMAT
C     **************************************************************
C     ***  THIS SUBROUTINE SETS UP THE CROSS SECTION MATRICES
C     **************************************************************
      COMMON/ALK/PIN(104),POUT(104),IZ(104),IA(104)
      COMMON/BLK/Q(104,104)
      COMMON/CLK/SDEX,RDEX,RP,EMAX,DX
      DIMENSION IQ(104)
C     **************************************************************
C     ***  READ IN PARTIAL CROSS SECTION DATA FROM Q.DAT
C     **************************************************************
      OPEN(UNIT=3,FILE='Q.DAT',READONLY,STATUS='OLD')
      DO J=1,104
        READ(3,1) (IQ(I),I=1,104)
 1      FORMAT(1X/,6(20I4/))
        DO I=1,104
          Q(I,J)=FLOAT(IQ(I))
        END DO
      END DO
C     **************************************************************
C     ***  REPLACE CROSS SECTIONS WITH RECIPROCAL MEAN FREE PATHS
C     **************************************************************
      FA=5.975E-4/14.42
      DO J=1,104
        DO I=1,104
          Q(I,J)=FA*DX*Q(I,J)
        END DO
      END DO
C     **************************************************************
C     ***  INCORPORATE PROTON-NUCLEUS TOTAL INELASTIC CROSS SECTION
C     **************************************************************
      C1=.79*44.9*14.**.7
      C2=.21*44.9*16.**.7
      Q(1,1)=1.+Q(1,1)-FA*DX*(C1+C2)
C     **************************************************************
C     ***  INCORPORATE NUCLEUS-NUCLEUS TOTAL INELASTIC CROSS SECTION
C     **************************************************************
      DO J=2,104
        C1=.79*(IA(J)**.333+14.**.333-.4)**2
        C2=.21*(IA(J)**.333+16.**.333-.4)**2
        Q(J,J)=1.+Q(J,J)-49.88*FA*DX*(C1+C2)
      END DO
      RETURN
      END


      SUBROUTINE ILOSS
C     **************************************************************
C     ***  THIS SUBROUTINE SETS UP THE IONIZATION LOSS VECTORS
C     **************************************************************
      COMMON/ALK/PIN(104),POUT(104),IZ(104),IA(104)
      COMMON/CLK/SDEX,RDEX,RP,EMAX,DX
      DIMENSION WL(104),W(104)
C     **************************************************************
C     ***  READ IN STOPPING POWER DATA FROM POWIN.DAT (FOR CURRENT
C     ***  ENERGY ONLY).
C     **************************************************************
      READ(4,1) E,DE,(W(J),J=1,104)
 1    FORMAT(F8.3,5X,F8.3,13(/8(1PE9.2)))
```

```
C       ************************************************************
C       ***  CALCULATE IONIZATION LOSS VECTORS USING HIGH-ENERGY
C       ***  APPROXIMATION IF ENERGY = EMAX, OR DERIVATIVE
C       ***  APPROXIMATION AT OTHER ENERGIES.
C       ************************************************************
        DEX=((SDEX-1.)*RDEX+1.)/RP*DX
        DER=1./DE
        EM=EMAX-.05
        IF (E.LE.EM) THEN
          DO J=1,104
            PIN(J)=WL(J)*DER*DX
            POUT(J)=1.-W(J)*DER*DX
          END DO
        ELSE
          DO J=1,104
            PIN(J)=0.
            POUT(J)=1.-FLOAT(IZ(J))**2*DEX/FLOAT(IA(J))
          END DO
        ENDIF
C       ************************************************************
C       ***  STORE STOPPING POWERS FOR CURRENT ENERGY IN WL(104) FOR
C       ***  USE AS 'PREVIOUS' STOPPING POWER NEXT TIME AROUND.
C       ************************************************************
        DO J=1,104
          WL(J)=W(J)
        END DO
        RETURN
        END
```

APPENDIX 7

```
      PROGRAM GRAM
C     ***********************************************************
C     ***  THIS PROGRAM CONVERTS PROPAGATES THE DIFFERENTIAL
C     ***  ENERGY FLUX THROUGH 1 GM/CM**2 MATERIAL TAKING INTO
C     ***  ACCOUNT ONLY IONIZATION LOSS.  IT ALSO EXTENDS THE
C     ***  MINIMUM ENERGY DOWN TO 1 MEV/AMU.
C     ***********************************************************
      DIMENSION FIN(26,28),FOUT(26,44),E(44),EP(26,44)
      DIMENSION F(4,28),EN(28),EQ(26,44)
C     *************************************************************
C     ***  READ IN FLUX FROM FOR010.DAT
C     *************************************************************
      DO II=1,28
        I=29-II
        READ(10,1) (FIN(J,I),J=1,26)
 1      FORMAT(4(7(1PE10.2)/))
      END DO
C     *************************************************************
C     ***  READ IN TABLES OF ENERGY PRIOR TO 1 GM AND ENERGY
C     ***  INTERVAL SPREAD FROM RANGIN.DAT.
C     *************************************************************
      OPEN(UNIT=7,FILE='RANGIN.DAT',READONLY,STATUS='OLD')
      DO I=1,44
        READ(7,1) E(I),(EP(J,I),J=1,26)
      END DO
      DO I=1,44
        READ(7,1) E(I),(EQ(J,I),J=1,26)
      END DO
      DO I=1,28
        EN(I)=E(I+16)
      END DO
      DO J=1,26
        DO  K=1,4
          F(K,J)=0.
        END DO
        DO I=1,28
          F(1,I)=FIN(J,I)
        END DO
        CALL CUBSPL(EN,F,28)
        DO I=1,4
          F(I,28)=F(I,27)
        END DO
        DO I=1,44
          ER=EP(J,I)
          DO KK=1,28
            K=29-KK
            IF(EN(K).LT.ER) GO TO 50
          END DO
          FOUT(J,I)=(((F(4,K)*ER+F(3,K))*ER+F(2,K))*ER+F(1,K))*
     &    EQ(J,I)
        END DO
      END DO
C     ***********************************************************
C     ***  OUTPUT DIFFERENTIAL FLUX IN FINAL FORM
C     ***********************************************************
      DO J=1,44
        WRITE(20,1) (FOUT(I,J),I=1,26)
      END DO
      END
```

APPENDIX 8

```
      PROGRAM ATMOS
C     ***************************************************************
C     ***  THIS PROGRAM CONVERTS DIRECTIONAL FLUXES ("OUT2") AT
C     ***  DEPTHS OF 0, 5, 15, 30, 50, 75, AND 100 GM/CM**2 IN
C     ***  THE ATMOSPHERE AND INTEGRATES THEM OVER ALL ANGLES TO
C     ***  GET THE TOTAL FLUX.  BOTH GEOMAGNETIC CUTOFF AND THE
C     ***  INCREASED GRAMMAGE AT NON-VERTICAL DIRECTIONS ARE
C     ***  INCLUDED.
C     ***  INPUT FILES ARE NAMED AFILE1 THROUGH AFILE7.
C     ***************************************************************
      DIMENSION F(26,44)
      COMMON/ALK/E(44),C(7,26,44)
C     ***************************************************************
C     ***  ENTER ALTITUDE AND CUTOFF, CALCULATE GRAMMAGE.
C     ***************************************************************
      ACCEPT *,ALTITUDE,CUTOFF
      CUTOFF=CUTOFF/10.
      CALL ALTGRM(ALTITUDE,GRAMS)
C     ***************************************************************
C     ***  ACCEPT FLUX DATA
C     ***************************************************************
      OPEN(UNIT=21,FILE='AFILE1.DAT',STATUS='OLD',READONLY)
      OPEN(UNIT=22,FILE='AFILE2.DAT',STATUS='OLD',READONLY)
      OPEN(UNIT=23,FILE='AFILE3.DAT',STATUS='OLD',READONLY)
      OPEN(UNIT=24,FILE='AFILE4.DAT',STATUS='OLD',READONLY)
      OPEN(UNIT=25,FILE='AFILE5.DAT',STATUS='OLD',READONLY)
      OPEN(UNIT=26,FILE='AFILE6.DAT',STATUS='OLD',READONLY)
      OPEN(UNIT=27,FILE='AFILE7.DAT',STATUS='OLD',READONLY)
      DO L=1,7
        LL=L+20
        DO K=1,44
          READ(LL,402) (C(L,I,K),I=1,26)
        END DO
      END DO
      CLOSE(UNIT=21)
      CLOSE(UNIT=22)
      CLOSE(UNIT=23)
      CLOSE(UNIT=24)
      CLOSE(UNIT=25)
      CLOSE(UNIT=26)
      CLOSE(UNIT=27)
C     ***************************************************************
C     ***  MAIN ROUTINE
C     ***************************************************************
      DO I=1,9
        THETA=FLOAT(I-1)*.174533
        GM=GRAMS/COS(THETA)
        DO J=1,12
          IF ((I.EQ.1.AND.J.EQ.1).OR.(I.GT.1)) THEN
            PHI=FLOAT(J-1)*.523599
            CUT=CUTFACT(CUTOFF,THETA,PHI)
            IF (I.GT.1) THEN
              AREA=.523988*(COS(THETA-.087267)-COS(THETA+.087267))
            ELSE
              AREA=.023909
            ENDIF
            DO K=1,26
              RESIDUAL=RANGE(1000.*CUTOFF,K)-GM
              DO L=44,1,-1
                IF(RANGE(E(L),K).GT.RESIDUAL) THEN
                  F(K,L)=F(K,L)+FLUX(GM,K,L)*AREA
```

```
              ENDIF
            END DO
          END DO
        ENDIF
      END DO
    END DO
    DO L=1,44
      WRITE(60,402) (P(K,L),K=1,26)
    END DO
402 FORMAT(4(7(1PE10.2)/))
    END


    SUBROUTINE ALTGRM(X,G)
C   ****************************************************************
C   ***  THIS SUBROUTINE CALCULATES THE GRAMMAGE CORRESPONDING TO
C   ***  A GIVEN VERTICAL ALTITUDE IN KILOFEET.
C   ****************************************************************
    ZGM=.04534-1.17E-9*ABS(X-105.)**3.58
    G=1033.*EXP(-ZGM*X)
    RETURN
    END


    FUNCTION RANGE(ENERGY,IZ)
C   ****************************************************************
C   ***  THIS FUNCTION CALCULATES THE RANGE OF CHARGED PARTICLES
C   ***  IN AIR (79% N/21% O) USING THE BETHE-BLOCH FORMULA.  THE
C   ***  CHARGE/MASS RATIO IS TAKEN AS 2.  ALL ENERGIES IN MEV/NUC.
C   ****************************************************************
    DIMENSION X(10),A(10),AMASS(26)
    DATA X/-.97390653,-.86506337,-.67940957,-.43339539,
  & -.14887434,.14887434,.43339539,.67940957,
  & .86506337,.97390653/
    DATA A/.06667134,.14945135,.21908636,.26926672,
  & .29552422,.29552422,.26926672,.21908636,
  & .14945135,.06667134/
    DATA AMASS/1.0079,4.0026,6.94,9.01218,10.81,12.011,
  & 14.0067,15.9994,18.9984,20.17,22.98977,24.305,26.98154,
  & 28.0855,30.974,32.06,35.453,39.948,39.0983,40.08,44.9559,
  & 47.90,50.9415,51.996,54.938,55.847/
C   ****************************************************************
C   ***  CALCULATE RANGE
C   ****************************************************************
    EO=10.
    RO=.145
    PARITY=1.
    IF(ENERGY.LT.EO) THEN
      Y=EO
      EO=ENERGY
      ENERGY=Y
      PARITY=-1.
    ENDIF
    SLOPE=.5*(ENERGY-EO)
    YINTERCEPT=.5*(ENERGY+EO)
    RANGE=RO
    IF (ENERGY.NE.EO) THEN
      DO J=1,10
        E=SLOPE*X(J)+YINTERCEPT
```

```
         RANGE=RANGE+A(J)*PARITY/STPOW(E)*SLOPE
       END DO
     ENDIF
     RANGE=AMASS(IZ)*RANGE/FLOAT(IZ)**2
     RETURN
     END


     FUNCTION STPOW(E)
C    ************************************************************
C    ***  THIS FUNCTION CALCULATES THE STOPPING POWER OF PROTONS IN
C    ***  AIR VS. ENERGY IN MEV.
C    ************************************************************
     GAMMA=1.+E/931.5
     B=1.-1./GAMMA**2
     X1=.15346*(ALOG(12463.*B/(1.-B))-B)/B
     X2=.15354*(ALOG(10376.*B/(1.-B))-B)/B
     STPOW=.76708*X1+.23292*X2
     RETURN
     END


     FUNCTION CUTFACT(CUTOFF,THETA,PHI)
C    ************************************************************
C    ***  THIS FUNCTION CALCULATES THE GEOMAGNETIC CUTOFF AT ZENITH
C    ***  ANGLE, THETA, AND AZIMUTHAL ANGLE, PHI.  A DIPOLE FIELD
C    ***  IS ASSUMED.  CALCULATION AT 20 KM.
C    ************************************************************
     FACT=59.6/(1.+20./6371.)**2
     COSL=(4.*CUTOFF/FACT)**.25
     COSG=COS(PHI)*SIN(THETA)
     A=(1.+SQRT(1.-COSG*COSL**3))**2
     CUTFACT=4.*CUTOFF/A
     RETURN
     END


     FUNCTION FLUX(GM,IZ,IE)
C    ************************************************************
C    ***  THIS FUNCTION INTERPOLATES THE FUNCTION C(7,26,44)
C    ***  TO GIVE ITS VALUE AT GRAMMAGE, GM.
C    ************************************************************
     DIMENSION D(7)
     COMMON/ALK/E(44),C(7,26,44)
     DATA E/1.,1.2,1.5,2.,2.5,3.,4.,5.,6.,7.,8.,10.,12.,15.,
    & 20.,25.,30.,40.,50.,60.,70.,80.,100.,120.,150.,200.,250.,
    & 300.,400.,500.,600.,700.,800.,1000.,1200.,1500.,2000.,
    & 2500.,3000.,4000.,5000.,6000.,7000.,8000./
     DATA D/0.,5.,15.,30.,50.,75.,100./
     DO J=1,6
       IF (GM.GE.D(J)) JX=J
     END DO
     IF (C(JX,IZ,IE).LE.0..OR.C(JX+1,IZ,IE).LE.0.) THEN
       FLUX=0.
     ELSE
       XX=C(JX,IZ,IE)/C(JX+1,IZ,IE)
       X=ALOG(XX)/(D(JX+1)-D(JX))
       IF (X*(GM-D(JX)).LT.15.) THEN
       FLUX=C(JX,IZ,IE)*EXP(-X*(GM-D(JX)))
     ELSE
       FLUX=0.
     ENDIF
   ENDIF
   RETURN
   END
```

APPENDIX 9

```
      PROGRAM LETINTT
C     ************************************************************
C     ***  THIS PROGRAM CALCULATES THE INTEGRAL LET SPECTRUM SUMMED
C     ***  OVER ALL ELEMENTS FROM A FLUX (OUTFILE.DAT) FILE.
C     ***  INPUT FILE NAMED FOR010.FOR
C     ***  OUTPUT FILE NAMED FOR020.FOR (USE PLOTT TO PLOT)
C     ************************************************************
      DIMENSION C(6,44),ZZ(28),IZ(28),S(4,44),XE(500),DXE(500)
      DIMENSION E(44),H(4,44),Q(26,44),A(27,4,500)
      DATA E1,E2/1.,8000./
      DATA ZZ/1.,2*2.,3*6.,7*8.,8*18.,7*26./
      DATA IZ/1,2*2,3*3,7*4,8*5,7*6/
      DO J=1,4
C     ************************************************************
C     ***  INITIALIZE SPLINE PARAMETER MATRICES
C     ************************************************************
        DO K=1,44
          S(J,K)=0.
          H(J,K)=0.
        END DO
C     ************************************************************
C     ***  INITIALIZE OUTPUT LET MATRIX
C     ***  K = CHARGE (FOR K=27, SUM OVER ALL CHARGES)
C     ***  J = SPECTRUM TYPE (1=INTEGRAL LET)
C     ***  L = DATA POINT
C     ************************************************************
        DO K=1,27
          DO L=1,500
            A(K,J,L)=0.
          END DO
        END DO
      END DO
C     ************************************************************
C     ***  READ SILICON STOPPING POWER
C     ************************************************************
      OPEN(UNIT=8,FILE='STPOW.DAT',READONLY,STATUS='OLD')
      DO J=1,44
        READ(8,1) E(J),(C(I,J),I=1,6)
 1      FORMAT(F8.3,6(3X,1PE9.3))
      END DO
C     ************************************************************
C     ***  READ IN FLUX DATA FROM FOR020.DAT
C     ************************************************************
      DO I=1,44
        READ(20,2) (Q(J,I),J=1,26)
 2      FORMAT(4(7(1PE10.2)/))
      END DO
C     ************************************************************
C     ***  DETERMINE ENERGY AND LET BIN WIDTH PARAMETERS
C     ************************************************************
      F1=(E2/E1)**.002
      F2=(1.-1./F1)*E1
      F3=.5*(1.+1./F1)*E1
      Q1=10.**.01
      Q2=1.-1./Q1
      DO I=1,500
        XE(I)=F3*F1**I
        DXE(I)=F2*F1**I
      END DO
C     ************************************************************
C     ***  PERFORM CALCULATIONS ON EACH ELEMENT FIRST
```

```
C       ****************************************************************
        DO J=1,26
C       ****************************************************************
C       ***  ESTABLISH FLUX POINTS TO BE SPLINE INTERPOLATED
C       ****************************************************************
          DO I=1,44
            H(1,I)=Q(J,I)
          END DO
          CALL CUBSPL(E,H,44)
C       ****************************************************************
C       ***  ESTABLISH STOPPING POWER POINTS TO BE SPLINE INTERPOLATED
C       ****************************************************************
          Z1=FLOAT(J)
          Z2=ZZ(J)
          IZZ=IZ(J)
          DO I=1,44
            AA=1./(1.+.001073927*E(I))**2
            B=SQRT(1.-AA)
            Z1E=Z1*(1.-EXP(-130.*B/Z1**.6667))
            Z2E=Z2*(1.-EXP(-130.*B/Z2**.6667))
            S(1,I)=(Z1E/Z2E)**2*C(IZZ,I)
          END DO
          CALL CUBSPL(E,S,44)
C       ****************************************************************
C       ***  FOR EACH BIN USE FLUX AND STOPPING POWER INTERPOLATIONS
C       ***  (PARAMETERS CONTAINED IN H AND S, RESPECTIVELY) TO GET
C       ***  INTEGRAL AND DIFFERENTIAL LET AND ENERGY SPECTRA.
C       ****************************************************************
          IDEX=1
          MDEX=1
          DO II=1,500
            I=501-II
            X=XE(I)
            DX=DXE(I)
            DO KK=IDEX,44
              K=45-KK
              IF(E(K).LE.X) GO TO 40
            END DO
 40         F=((H(4,K)*X+H(3,K))*X+H(2,K))*X+H(1,K)
            IDEX=KK
            DO KK=MDEX,44
              K=45-KK
              IF(E(K).LE.X) GO TO 60
            END DO
 60         SP=((S(4,K)*X+S(3,K))*X+S(2,K))*X+S(1,K)
            MDEX=KK
            A(J,4,I)=A(J,4,I)+F
            DO K=1,I
              A(J,3,K)=A(J,3,K)+F*DX
            END DO
            L=1+INT(100.*ALOG10(SP))
            DL=Q2*Q1**L
            Q=F*DX/DL
            QP=F*DX
            A(J,2,L)=A(J,2,L)+Q
            A(27,2,L)=A(27,2,L)+Q
            DO K=1,L
              A(J,1,K)=A(J,1,K)+QP
              A(27,1,K)=A(27,1,K)+QP
            END DO
          END DO
```

```
C       **************************************************************
C       ***  ADD HIGHEST ENERGY COSMIC RAYS TO LET SPECTRA
C       **************************************************************
          GP=(Z1/Z2)**2*C(IZZ,44)
          L=1+INT(100.*ALOG10(SP))
          DL=Q2*Q1**L
          Q=Q(J,44)*E2/1.5/DL
          QP=Q(J,44)*E2/1.5
          A(J,2,L)=A(J,2,L)+Q
          A(27,2,L)=A(27,2,L)+Q
          DO K=1,L
            A(J,1,K)=A(J,1,K)+QP
            A(27,1,K)=A(27,1,K)+QP
          END DO
          DO K=1,500
            A(J,3,K)=A(J,3,K)+QP
          END DO
        END DO
C       **************************************************************
C       ***  DETERMINE LET VALUES AND INTEGRAL LET SPECTRUM VALUES
C       ***  AND OUTPUT TO FOR030.DAT.
C       **************************************************************
        QLET=10.**.01
        DO I=1,500
          QPLET=QLET**I
          SPLET=A(27,1,I)
          WRITE(30,666) SPLET,QPLET
        END DO
 666    FORMAT(2X,E12.5,2X,E12.5)
        END
```

APPENDIX 10

```
      PROGRAM UPSET
C     ************************************************************
C     ***  THIS PROGRAM CONVERTS A FLUX VS. LET SPECTRUM INTO AN
C     ***  UPSET/KILOBIT/DAY VS. CRITICAL CHARGE PLOT.
C     ***  REQUIRED INPUT:
C     ***      X,Y,Z = DIMENSIONS OF SENSITIVE VOLUME
C     ***  REQUIRED FILES.
C     ***      FOR030.DAT = LET SPECTRUM FROM LETINTT
C     ***      FOR040.DAT = OUTPUT UPSET PROBABILITIES
C     ************************************************************
      DIMENSION FLUX(500),PC(500),ER(500),DL(500),DD(500)
      REAL L(500),LMIN
      DSI=2.321
C     ************************************************************
C     ***  ACCEPT DIMENSIONS OF SENSITIVE VOLUME (MICRONS)
C     ************************************************************
      ACCEPT *,X,Y,Z
C     ************************************************************
C     ***  COMPUTE MEAN PROJECTED SURFACE AREA, CONVERT TO PROPER
C     ***  UNITS.
C     ************************************************************
      S=(2.*X*Y+2.*Y*Z+2.*Z*X)*1.E-12      ! M**2
      X=X*.0001*DSI    ! GRAMS/CM**2
      Y=Y*.0001*DSI    ! GRAMS/CM**2
      Z=Z*.0001*DSI    ! GRAMS/CM**2
      PMAX=SQRT(X*X+Y*Y+Z*Z)   ! MAX. PATHLENGTH (GM/CM**2)
C     *************************************************************
C     ***  READ LET SPECTRUM
C     *************************************************************
      DO J=1,500
        READ(30,400) FLUX(J),L(J)
        IF (FLUX(J).LT.0.) FLUX(J)=0.
 400    FORMAT(2(2X,E12.5))
      END DO
C     ************************************************************
C     ***  COMPUTE DIFFERENTIALS
C     ************************************************************
      G1=10.**.01
      G2=1.-1./G1
      DO J=1,500
        DL(J)=G2*G1**J/L(J)**2
      END DO
C     *************************************************************
C     ***  COMPUTE PATHLENGTH TERMS
C     *************************************************************
      DO J=1,500
        RAT=10.**(.01*FLOAT(1-J)) ! RATIO OF TWO STOPPING POWERS
        DD(J)=DIFPLD(PMAX*RAT,X,Y,Z)
      END DO
C     ************************************************************
C     ***. COMPUTE UPSETS
C     ************************************************************
      DO J=1,500
        QCRIT=PMAX*L(J)/22.5
        PC(J)=QCRIT
        FACT=22.5*QCRIT
        SUM=0.
        DO I=J,500
          SUM=SUM+DL(I)*FLUX(I)*DD(I-J+1)
        END DO
        ER(J)=SUM*FACT*S*.25*86400.*1024
```

```
      END DO
C     ****************************************************************
C     ***  OUTPUT UPSET RATES
C     ****************************************************************
      DO J=1,500
        WRITE(40,400) ER(J),PC(J)
      END DO
      END


      FUNCTION DIFPLD(S,L,W,H)
      REAL L
      AP=3.*(H*W+H*L+L*W)
      DIFPLD=(Q(S,L,W,H)+Q(S,W,L,H)+Q(S,L,H,W)+Q(S,W,H,L)+
     *  Q(S,H,W,L)+Q(S,H,L,W))/(3.1416*AP)
      END


      FUNCTION Q(S,X,Y,Z)
      REAL KSQ
      KSQ=X*X+Y*Y
      TSQ=X*X+Z*Z
      T=SQRT(TSQ)
      RSQ=KSQ+Z*Z
      R=SQRT(RSQ)
      V=12.*X*Y*Z*Z
      PSQ=S*S-Z*Z
      QSQ=S*S-X*X-Z*Z
      IF((S.GE.0.0).AND.(S.LT.Z)) GO TO 10
      IF((S.GE.Z) .AND.(S.LT.T))  GO TO 20
      IF((S.GE.T) .AND.(S.LE.R))  GO TO 30
      Q=0.0
      RETURN
10    Q=8.*Y*Y*Z/KSQ-S*(3.*X*Y/(R*T))*
      RETURN
20    Q=S*(3.*Y/SQRT(KSQ))**2-S*(3.*X*Y/(T*R))**2
     * -X*(SQRT(PSQ)/S)*(8.+4.*Z*Z/(S*S))
     * +(V*ATAN(Y/X)-(Y*Z*Z/SQRT(KSQ))**2)/(S*S*S)
      RETURN
30    Q=-S*(3.*X*Z/(R*SQRT(KSQ)))**2
     * +(X*X*Z*Z*(Z*Z/KSQ-3.)+V*ATAN(Y/X))/(S*S*S)
     * +Y*Z*Z*(SQRT(QSQ)/S)*(8./TSQ+4./(S*S))
     * -(V/(S*S*S))*ACOS(X/SQRT(PSQ))
      END
```

```
$ !      ZCOM.COM IS A COMMAND FILE GENERATING PROGRAM DESIGNED
$ !      FOR USE ON THE VAX MINICOMPUTER.  THIS PROGRAM WAS WRITTEN
$ !      IN JANUARY, 1983 BY JOHN R. LETAW, SEVERN COMMUNICATIONS
$ !      CORP., SEVERNA PARK, MD.
$ !
$ !      GREETING
$ WRITE SYS$OUTPUT "THIS COMMAND FILE CREATES A COMMAND FILE WHICH",-
   " WILL EXECUTE PROPAGATION IN"
$ WRITE SYS$OUTPUT "AIR PROGRAMS.  ALL INPUT PARAMETERS",-
   " ARE DETERMINED BY YOUR ANSWERS"
$ WRITE SYS$OUTPUT "TO THE PROMPTS.  PRESERVE THIS SESSION FOR ",-
   "FUTURE REFERENCE"
$ WRITE SYS$OUTPUT " "
$ !      COMMAND FILE NAME
$ INQUIRE COMFILE "ENTER COMMAND FILE NAME"
$ OPEN/WRITE OUTF 'COMFILE'
$ WRITE SYS$OUTPUT " "
$ !      COMMAND FILE DEFAULTS
$ WRITE OUTF "$ SET DEFAULT [LETAW.TEMP]"
$ WRITE OUTF "$ ASSIGN INL: SYS$PRINT"
$ !      INPUT FLUX
$ WRITE SYS$OUTPUT "CALCULATE INPUT FLUX"
$ INQUIRE YEAR "ENTER YEAR (1975.144=MIN,1980.598=MAX)"
$ INQUIRE WEATHER "ENTER WEATHER (1=GALACTIC COSMIC RAYS)"
$ ORBITER=0
$ WRITE OUTF "$ DELETE FLUXES.DAT;*"
$ WRITE OUTF "$ FOR FLUX"
$ WRITE OUTF "$ LIN FLUX"
$ WRITE OUTF "$ RUN FLUX"
$ WRITE OUTF YEAR," ",WEATHER," ",ORBITER
$ WRITE OUTF "$ DELETE FLUX.OBJ;*,FLUX.EXE;*,FLUX.LIS;*,FLUX.MAP;*"
$ WRITE SYS$OUTPUT "OUTFILEO.DAT CONTAINS THE INPUT FLUX."
$ PCOUNT=0  !      INITIALIZE NUMBER OF PROPAGATIONS
$ SUMGRAMS=0  !      INITIALIZE TOTAL GRAMMAGE
$ QCOUNT=0  !      INITIALIZE NUMBER OF POST-PROCESSED FILES
$ !      ASSIGN PROPAGATION MEDIUM TO AIR
$ WRITE OUTF "$ DELETE PROP.*;*,RANGIN.DAT;*"
$ WRITE OUTF "$ DELETE POWIN.DAT;*,Q.DAT;*"
$ WRITE OUTF "$ COPY APROP.FOR;1 PROP.FOR;1"
$ WRITE OUTF "$ COPY ARANGIN.DAT;1 RANGIN.DAT;1"
$ WRITE OUTF "$ COPY APOWIN.DAT;1 POWIN.DAT;1"
$ WRITE OUTF "$ COPY AQ.DAT;1 Q.DAT;1"
$ WRITE OUTF "$ FOR PROP"
$ WRITE OUTF "$ LIN PROP"
$ WRITE OUTF "$ FOR GRAM"
$ WRITE OUTF "$ FOR CUBSPL"
$ WRITE OUTF "$ LIN GRAM,CUBSPL"
$ WRITE OUTF "$ FOR REFORM"
$ WRITE OUTF "$ LIN REFORM"
$ PM:
$ PCOUNT=PCOUNT+1
$ !      DETERMINE GRAMMAGE
$ WRITE SYS$OUTPUT " "
$ INQUIRE GRAMS "ENTER NUMBER OF GRAMS OF AIR (>1)"
$ SUMGRAMS=SUMGRAMS+GRAMS
$ !      PROP EXECUTION
$ WRITE OUTF "$ RUN PROP"
$ WRITE OUTF GRAMS
$ WRITE OUTF "$ DELETE PROP.LIS;*,PROP.MAP;*"
$ !      GRAM EXECUTION
$ WRITE OUTF "$ DELETE FOR020.DAT;*"
```

```
$ WRITE OUTF "$ RUN GRAM"
$ WRITE OUTF "$ DELETE GRAM.LIS;*,GRAM.MAP;*"
$ !      ESTABLISH OUTPUT FILE
$ OUTFILE = "OUTFILE"+F$STRING(PCOUNT)+".DAT"
$ WRITE OUTF "$ COPY FOR020.DAT ",OUTFILE
$ WRITE SYS$OUTPUT " "
$ WRITE SYS$OUTPUT OUTFILE," CONTAINS THE FLUX AFTER ",SUMGRAMS,-
    " GRAMS."
$ !      BRANCH FOR FURTHER PROPAGATIONS
$ INQUIRE MORE "DO YOU WANT TO CONTINUE PROPAGATION? (Y/N)"
$ IF MORE.EQS."N" THEN GOTO POST
$ WRITE OUTF "$ DELETE FLUXES.DAT;*"
$ WRITE OUTF "$ RUN REFORM"
$ WRITE OUTF "$ DELETE REFORM.MAP;*,REFORM.LIS;*"
$ GOTO PM
$ !      POST-PROCESSING
$ POST:
$ WRITE SYS$OUTPUT " "
$ INQUIRE MORE "DO YOU WANT TO DO ANY POST-PROCESSING? (Y/N)"
$ IF MORE.EQS."N" THEN GOTO END
$ !      POST-PROCESSING OPTION SELECTION
$ WRITE SYS$OUTPUT " "
$ WRITE SYS$OUTPUT -
  "AT THIS POINT THERE ARE SEVERAL POST-PROCESSING OPTIONS"
$ WRITE SYS$OUTPUT "  1)  OMNIDIRECTIONAL ATMOSPHERIC INTEGRATION"
$ WRITE SYS$OUTPUT "  2)  INTEGRAL LET SPECTRUM (TOTAL)"
$ WRITE SYS$OUTPUT "  3)  INTEGRAL LET SPECTRUM (BY ELEMENT GROUP)"
$ WRITE SYS$OUTPUT "  4)  SOFT UPSET RATE"
$ WRITE SYS$OUTPUT "  5)  EXIT"
$ INQUIRE PROCESS "SELECT ONE OPTION"
$ !      OPTION DISTRIBUTION (1 AND 4)
$ IF PROCESS.EQS.1 THEN GOTO POST1
$ IF PROCESS.EQS.4 THEN GOTO POST4
$ WRITE OUTF "$ DELETE STPOW.DAT;*"
$ WRITE OUTF "$ COPY SILPOW.DAT;1 STPOW.DAT;1"
$ GOTO PRODIST
$ !      OPTION DISTRIBUTION (2, 3, AND 5)
$ PRODIST:
$ IF PROCESS.EQS.2 THEN GOTO POST2
$ IF PROCESS.EQS.3 THEN GOTO POST3
$ IF PROCESS.EQS.5 THEN GOTO END
$ GOTO POST
$ POST1:
$ !      ATMOSPHERIC INTEGRATION UP TO 100 GMS (53,000 FT.)
$ WRITE SYS$OUTPUT " "
$ WRITE SYS$OUTPUT "SEVEN FILES CONTAINING THE FLUXES AT 0, 5,",-
    " 15, 30, 50, 75, AND 100 "
$ WRITE SYS$OUTPUT "GRAMS/CM**2 RESPECTIVELY ARE REQUIRED."
$ COUNTER=0
$ COUNT2:
$ COUNTER=COUNTER+1
$ IF COUNTER.EQ 8 THEN GOTO XCOUNT2
$ INQUIRE S "ENTER FILE"
$ SS="AFILE"+F$STRING(COUNTER)+".DAT"
$ WRITE OUTF "$ DELETE ",SS,";*"
$ WRITE OUTF "$ COPY ",S," ",SS
$ GOTO COUNT2
$ XCOUNT2:
$ WRITE OUTF "$ FOR ATMOS"
$ WRITE OUTF "$ LIN ATMOS"
$ CDEEP=0
```

```
$ DEPTH2:
$ INQUIRE ALTITUDE "ENTER ALTITUDE IN ATMOSPHERE IN KILOFEET"
$ INQUIRE CUTOFF "ENTER CUTOFF TIMES 10 IN GV"
$ CDEEP=CDEEP+1
$ SS="ATM"+F$STRING(ALTITUDE)+"."+F$STRING(CUTOFF)
$ WRITE SYS$OUTPUT SS," CONTAINS THE FLUX AT ",ALTITUDE," KILOFEET ",-
     "WITH A ",CUTOFF,"/10 GV CUTOFF "
$ WRITE OUTF "$ RUN ATMOS"
$ WRITE OUTF ALTITUDE,"  ",CUTOFF
$ WRITE OUTF "$ COPY FOR060.DAT ",SS
$ INQUIRE MORE "ANOTHER ALTITUDE AND CUTOFF?  (Y/N)"
$ IF MORE.EQS."Y" THEN GOTO DEPTH2
$ WRITE OUTF "$ DELETE AFILE*.*;*,FOR060.DAT;*"
$ WRITE OUTF "$ DELETE ATMOS.EXE;*,ATMOS.OBJ;*,ATMOS.MAP;*,ATMOS.LIS;*"
$ GOTO POST
$ POST2:
$ !      TOTAL INTEGRAL LET SPECTRUM
$ WRITE OUTF "$ COPY LETINTT.FOR;1 LET.FOR;1"
$ GOTO CONT
$ POST3:
$ !      INTEGRAL LET SPECTRUM BY ELEMENT GROUP
$ WRITE OUTF "$ COPY LETINTG.FOR;1 LET.FOR;1"
$ GOTO CONT
$ POST4:
$ !      SOFT UPSET RATE
$ WRITE SYS$OUTPUT " "
$ WRITE SYS$OUTPUT "CONVERT AN INTEGRAL LET FILE INTO SOFT UPSET RATE"
$ WRITE SYS$OUTPUT " "
$ WRITE OUTF "$ FOR UPSET"
$ WRITE OUTF "$ LIN UPSET"
$ COUNTER=0
$ COUNT:
$ COUNTER=COUNTER+1
$ SS="EFILE"+F$STRING(COUNTER)+".DAT"
$ INQUIRE S "INTEGRAL LET FILE"
$ WRITE SYS$OUTPUT " "
$ WRITE OUTF "$ DELETE FOR030.DAT;*"
$ WRITE OUTF "$ COPY ",S," FOR030.DAT;1"
$ WRITE OUTF "$ DELETE FOR040.DAT;*"
$ WRITE SYS$OUTPUT "INPUT DIMENSIONS OF SENSITIVE REGION (MICRONS)"
$ INQUIRE DIM1 "LENGTH"
$ INQUIRE DIM2 "WIDTH "
$ INQUIRE DIM3 "DEPTH "
$ WRITE SYS$OUTPUT " "
$ WRITE OUTF "$ RUN UPSET"
$ WRITE SYS$OUTPUT "UPSET RATE FOR ",S," IS IN ",SS
$ WRITE OUTF DIM1," ",DIM2," ",DIM3
$ WRITE SYS$OUTPUT " "
$ WRITE OUTF "$ COPY FOR040.DAT ",SS
$ WRITE OUTF "$ DELETE FOR040.DAT;*,FOR030.DAT;*"
$ WRITE OUTF "$ DELETE UPSET.LIS;*,UPSET.MAP;*"
$ INQUIRE MORE "MORE UPSET CALCULATIONS? (Y/N)"
$ WRITE SYS$OUTPUT " "
$ IF MORE.EQS."Y" THEN GOTO COUNT
$ WRITE OUTF "$ DELETE UPSET.EXE;*,UPSET.OBJ;*"
$ GOTO POST
$ CONT:
$ WRITE OUTF "$ FOR LET"
$ WRITE OUTF "$ FOR CUBSPL"
$ WRITE OUTF "$ LIN LET,CUBSPL"
$ PFILES:
```

APPENDIX 10 (Cont'd)

```
$ WRITE SYS$OUTPUT " "
$ INQUIRE FILENAME "FILE TO BE PROCESSED"
$ QCOUNT=QCOUNT+1
$ WRITE OUTF "$ DELETE FOR020.DAT;*"
$ WRITE OUTF "$ COPY ",FILENAME," FOR020.DAT;1"
$ WRITE OUTF "$ RUN LET"
$ POSFILE = "PFILE"+F$STRING(QCOUNT)+".DAT"
$ WRITE OUTF "$ COPY FOR030.DAT;1 ",POSFILE
$ WRITE OUTF "$ DELETE FOR030.DAT;*"
$ WRITE SYS$OUTPUT FILENAME," WAS PROCESSED INTO ",POSFILE
$ INQUIRE MORE "ANY MORE FILES TO BE PROCESSED THIS WAY? (Y/N)"
$ IF MORE.EQS."Y" THEN GOTO PFILES
$ WRITE OUTF "$ DELETE LET.*;*,CUBSPL.OBJ;*,CUBSPL.LIS;*"
$ GOTO POST
$ END:
$ WRITE OUTF "$ DELETE FOR*.*;*,STPOW.DAT;*"
$ CLOSE OUTF
$ EXIT
```